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Evaluating The Effect Of Large Magnitude Earthquakes On Thermal Volcanic Activity: A Comparative Assessment Of The Parameters And Mechanisms That Trigger Volcanic Unrest And Eruptions

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Evaluating the Effect of Large Magnitude Earthquakes on Thermal Volcanic Activity: A Comparative Assessment of the Parameters and Mechanisms That Trigger Volcanic Unrest and Eruptions

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ABSTRACT

Volcanic eruptions and unrest have the potential to have large impacts on society causing social, economic and environmental losses. One of the primary goals of volcanological studies is to understand a volcano's behaviour so that future instances of unrest or impending eruptions can be predicted. Despite this, our ability to predict the onset, location and size of future periods of unrest remains inadequate and one of the main problems in forecasting is associated with the inherent complexity of volcanoes. In practice, most reliable forecasts have employed a probabilistic approach where knowledge of volcanic activity triggers have been incorporated into scenarios to indicate the probability of unrest. The proposed relationship between large earthquakes and volcanic activity may, therefore, indicate an important precursory signal for volcanic activity forecasting.

There have been numerous reports of a spatial and temporal link between volcanic activity and high magnitude seismic events and it has been suggested that significantly more periods of volcanic unrest occur in the months and years following an earthquake than expected by chance. Disparities between earthquake-volcano assessments and variability between responding volcanoes, however, has meant that the conditions that influence a volcano's response to earthquakes have not been determined. Using data from the MODVOLC algorithm, a proxy for volcanic activity, this research examined a globally comparable database of satellite-derived volcanic radiant flux to identify significant changes in volcanic activity following an earthquake. Cases of potentially triggered volcanic activity were then analysed to identify the earthquake and volcano parameters that influence the relationship and evaluate the mechansisms proposed to trigger volcanic activity following an earthquake.

At a global scale, this research identified that 57% [8 out of 14] of all large magnitude earthquakes were followed by increases in global volcanic activity. The most significant change in volcanic radiant flux, which demonstrates the potential of large earthquakes to influence volcanic activity at a global scale, occurred between December 2004 and April 2005. During this time, new thermal activity was detected at 10 volcanoes and the total daily volcanic radiant flux doubled within 52 days. Within a regional setting, this research also identified that instances of potentially triggered volcanic activity were statistically different to instances where no triggering was observed. In addition, assessments of earthquake and volcano parameters identified that earthquake fault characteristics increase the probability of triggered volcanic activity and variable response proportions at individual volcanoes and regionally demonstrated the critical role of the state of the volcanic system in determining if a volcano will respond. Despite the identification of these factors, this research was not able to define a model for the prediction of volcanic activity following earthquakes and, alternatively, proposed a process for response. In doing so, this thesis confirmed the potential use of earthquakes as a precursory indicator to volcanic activity and identified the most likely mechanisms that lead to seismically triggered volcanic unrest.

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LIST OF ABBREVIATIONS

AIRS	Atmospheric Infrared Sounder
ALOS	Advanced Land Observing Satellite
ANOVA	Analysis of Variance Test
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
β-statistic	Number of standard deviations from which the rate of the number of erupting volcanoes differs from the expected background estimate
CART	Classification and Regression Trees
CMT	Centroid Moment Tensor
ENVISAT	Environmental Satellite
E_f	Radiant Flux
EOS	Earth Observing System
EP TOMS	Earth Probe Total Ozone Mapping Spectrometer
ERS	European Remote Sensing Satellite
FRE	Fire Radiative Energy
GOES	Geostationary Operational Environmental Satellite
GVP	Smithsonian Global Volcanism Program
HIGP	Hawai'i Institute of Geophysics and Planetology
InSAR	Interferometric Synthetic Aperture Radar
IR	Infrared
J	Earthquake Seismic Energy Measured in Joules
LST	Land Surface Temperature
M	Earthquake Magnitude
MIR	Middle Infrared
MOD11	MODIS Land Surface Temperature and Emissivity Product (also MYD11)
MOD14	MODIS Thermal Anomaly Products
MODIS	Moderate Resolution Imaging Spectroradiometer
MODVOLC	Algorithm to map global distribution of volcanic thermal anomalies in near-real time using MODIS data
MW	Radiative Power Measured in Megawatts
N_a	Average number of erupting volcanoes following an earthquake

N_b	Average number of erupting volcanoes preceding an earthquake
NASA	National Aeronautics and Space Administration
NEIC	National Earthquake Information Centre
NR	Non-Triggered Earthquake-Volcano Interactions
NTI	Normalised Thermal Index
R	Triggered Earthquake-Volcano Interactions
TIR	Thermal Infrared
TW	Radiative Power Measured in Terawatts
USGS	United State Geological Survey
v	Average Volcanic Radiant Flux
$v + 1\sigma$	Inter-Annual Variability in Volcanic Radiant Flux
y	Objective Field in Machine Learning Analyses
σ	1-Standard Deviation of Volcanic Radiant Flux

CHAPTER 1

INTRODUCTION

Volcanic eruptions and unrest can have serious impacts on society causing social, economic and environmental losses (Marzocchi and Bebbington 2012). A primary goal, therefore, is to identify the factors that underlie unrest to determine how and why a volcano erupts and use this information for hazard mitigation and warning (Harris and Ripepe 2007; Marzocchi and Bebbington 2012; Phillipson *et al*. 2013; Pyle *et al*. 2013). Indeed, this need to provide accurate and timely forecasts has been recognised globally and since the 2004 Boxing Day earthquake and subsequent tsunami there have been increasing pressures to provide forecasts and predictions through the 'Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters' (UN-ISDR 2005). Large uncertainties within a volcanic system and a lack of understanding of the factors that lead to volcanic unrest, however, have meant that any attempts to predict the onset, location or size of impending eruptions have, so far, been practically impossible (Solid Earth Science Working Group 2002; Huppert and Sparks 2006; Marzocchi and Bebbington 2012; Pyle *et al*. 2013).

Previous attempts to forecast volcanic activity have focused on the use of operational models that provide probabilities of activity to issue effective warnings (Sparks and Aspinall 2004; Selva *et al*. 2012; Cañón-Tapia 2014). Estimates of probability, however, are subjective and research is required to identify indicators to volcanic activity as well as understand the uncertainties within a volcanic system (McNutt 2002; Sparks 2003; Huppert and Sparks 2006; De La Cruz-Reyna and Tilling 2008; Marzocchi and Bebbington 2012; Selva *et al*. 2012).

In order to improve our forecasting capabilities, therefore, it is important to identify and understand all potential triggers of volcanic activity (Huppert and Sparks 2006; Manga and Brodsky 2006; Hooper *et al*. 2012; Cañón-Tapia 2014; Gill and Malamud 2014). Internally, volcanic seismicity or deformation may indicate a period of unrest that reflects the injection of new magma or magma movement while changes in gas emissions and thermal activity may indicate a rising magma body (Kilburn 2003; Kilburn and Sammonds 2005; Hooper *et al*. 2012; Pyle *et al*. 2013). Alternatively, Cañón-Tapia (2014) and Gill and Malamud (2014) showed that volcanoes have one of the highest potentials to be triggered by external processes such as ice unloading or changes in tides and as secondary hazards following landslides or tsunamis (Figure 1-1). However, like periods of unrest, not all triggers will result in eruptive activity or conversely, eruptions will take place with no precursory activity (Cañón-Tapia 2014). Therefore, there is a need to assess the relative importance of these triggers to identify their significance as well as their forecasting capability.

Figure 1-1 Hazard interactions. There are 11 instances where the probability of volcanic hazards is increased or directly triggered by a primary hazard (Source: Gill and Malamud 2014: 693).

Commencing with an outline of the proposed relationship between earthquakes and volcanic activity (Section 1-1), this chapter introduces the main focus of this thesis to examine the significance of the relationship and assess the use of earthquakes as a precursory indicator to volcanic activity. A brief discussion of the advantages of satellite remote sensing for volcanology will be provided along with the utility of thermal infrared remote sensing to study the thermal response of volcanoes to earthquakes (Section 1-2). On the basis of the advantages and limitations of current earthquake-volcano investigations, the aims and objectives of this PhD will be described (Section 1-3) and the overall structure of this thesis outlined (Section 1-4).

1-1 EARTHQUAKE-VOLCANO INTERACTIONS

Mounting evidence of triggered volcanic activity following large magnitude earthquakes around the world has the potential to provide valuable insights into the processes that initiate a response for volcanic activity prediction and the identification of precursors (Hill *et al*. 1993; Linde and Sacks 1998; Hill *et al*. 2002; Manga and Brodsky 2006; Walter 2007; Eggert and Walter 2009; Bebbington and Marzocchi 2011; Lupi and Miller 2014; Bonali *et al*. 2015). Earliest published reports of a link between earthquakes and volcanoes identified increases in volcanic activity following the 1835 Concepión earthquake in South America (Darwin 1840). Since this time, research has focused on identifying increases in volcanic activity following earthquakes to identify the processes that lead to unrest. As a result, it has been suggested that significantly more eruptions occur in the months and years following earthquakes than expected by chance with 0.4% of explosive eruptions occurring within a few days of a large magnitude seismic event (Linde and Sacks 1998; Manga and Brodsky 2006; Watt *et al*. 2009; Battaglia *et al*. 2012).

The variability of the relationship at different spatial and temporal scales, however, presents one of the most prominent challenges in the study of earthquake-volcano interactions. While some volcanoes may show immediate signs of volcanic unrest (e.g. seismicity, deformation or fumarole activity) followed by a return to background activity, the majority of volcanoes exhibit signs of volcanic activity triggering weeks to months following an earthquake (e.g. Manga and Brodsky 2006; Battaglia *et al*. 2012; Prejean and Haney 2014; Walter and Woith 2014). Equally, responses have been observed at global scales (e.g. following the 2004 M9.1 Boxing Day earthquake), within a regional setting up to distances of 1,000 km and at a local scale (i.e. > 100 km) (Hill *et al*. 2002; Eggert and Walter 2009). There is a need, therefore, to identify a standardised method to examine the response of volcanoes to earthquakes so that the conditions that lead to seismically triggered unrest can be determined.

Although quantitative assessments of earthquake-volcano interactions have been conducted, there is still debate on the physical processes that lead to triggering and, as such, the mechanisms that control any relationship remain enigmatic (Brodsky *et al*. 1998; Hill *et al*. 2002; Walter and Amelung 2006; Delle Donne *et al*. 2010; Farías *et al*. 2014). Most often, changes in stress relating to an earthquake are thought to influence volcanoes in a critical state causing an increase in activity, often under conditions of clock advance (i.e. advancing the onset of an eruption that would have occurred without an earthquake trigger) (Hill *et al*. 2002; Bebbington and Marzocchi 2011). Therefore, as well as determining the conditions that lead to triggering, this thesis will provide an evaluation of the mechanism(s) suggested to influence a volcano's response.

The availability of appropriate and comparable data is another issue that has hampered assessments of the relationship between earthquakes and volcanoes. Research by Harris and Ripepe (2007) and Delle Donne *et al*. (2010) using MODVOLC, a volcanic thermal anomaly detection system, detected thermal anomalies to investigate the response of volcanoes to earthquakes highlights the potential use of remotely sensed data to monitor any relationship. Like assessments using ground-based observations, however, research is required to address the effective use of remotely sensed data to identify potentially triggered activity and establish appropriate methods for analysis.

1-2 VOLCANIC REMOTE SENSING

With over 1,500 potentially active volcanoes across the globe and more than 50 eruptions (on average) each year, there is a need for accurate and real-time analysis of volcanic hazards to minimise their impact on society (Harris *et al*. 1997; Webley *et al*. 2008; Wylie 2009; Chen *et al*. 2012). Arguably, one of the largest challenges faced by researchers are the risks associated with ground-based measurements (Rothery *et al*. 1988; Ramsey and Flynn 2004). Remote sensing technologies, therefore, present a unique and crucial application to monitor and assess the risks posed by volcanic activity where information would otherwise be absent (Francis and Rothery 1987; Rothery *et al*. 1988; Glaze *et al*. 1989; Harris *et al*. 1997; Tralli *et al*. 2005; Chen *et al*. 2012; Hooper *et al*. 2012). Further examples of the advantages of remote sensing for volcanology include:

- The provision of remotely sensed data which could supplement or even replace ground-based measurements (Glaze *et al*. 1989; Harris *et al*. 1997; Harris *et al*. 2000; Pyle *et al*. 2013);
- The provision of spatially continuous, near real-time imagery including information on volcanoes that are too remote, inaccessible or inactive to justify regular ground-based monitoring (Harris *et al*. 2000; Tralli *et al*. 2005; Kervyn *et al*. 2008; Hooper *et al*. 2012);

- The provision of timely information regarding the onset of eruptions which would otherwise go unrecorded (Harris *et al*. 2000; Steffke and Harris 2011);
- The availability of data which may provide insight into earth's surface processes, tectonic movements and volcanic hazards (Rothery *et al*. 1988; Tralli *et al*. 2005; Marchese *et al*. 2010); and,
- The ability to monitor changes in behaviour and identify impending eruptions (Rothery *et al*. 1988; Marchese *et al*. 2010; Harris *et al*. 2011; Blackett 2013).

Despite these advantages, no sensor has yet been designed or specifically intended for volcanic hazard assessment (Blackett 2014). The ability to exploit sensor capabilities to monitor changes in volcanic activity using visual, radar and infrared wavelengths, however, has seen volcanic remote sensing become an increasingly important and indispensable tool for volcanic activity monitoring, Figure 1-2 (Hooper *et al*. 2012; Pyle *et al*. 2013). What is more, the development of algorithms that use a sequence of automated calculations and defined thresholds to assess a range of volcanic features in near real-time means that it is possible to routinely monitor volcanoes on a local, regional and global scale (Oppenheimer 1998; Francis and Rothery 2000; Kaneko *et al*. 2002; Ramsey and Flynn 2004; Tralli *et al*. 2005; Hawbaker *et al*. 2008; Joyce *et al*. 2009; Steffke and Harris 2011; Blackett 2013).

FIGURE 1-2 INCREASED USE OF REMOTELY SENSED DATA TO MONITOR AND ASSESS VOLCANIC HAZARDS, 1991-2011 (SOURCE: PYLE *ET AL*. 2013: 8).

In context of the study of earthquake-volcano interactions, examples of the proven utility of remotely sensed data to investigate any relationship are identified in Section 2-3-6 (pg. 34). Specifically, this thesis harnesses the advantages of thermal infrared remote sensing (Section 2-5, pg. 48) which detects the radiation emitted by volcanoes reflecting eruptive activity, increases in thermal unrest or rising magma (Steffke and Harris 2011; Blackett 2013). In particular, the use of thermal infrared remote sensing will allow the potential relationship between earthquakes and volcanoes to be assessed at varying spatial and temporal scales as well as identifying globally comparable instances of earthquake-volcano interactions (Steffke and Harris 2011).

1-3 AIMS AND OBJECTIVES

The principle aim of this thesis is to examine the thermal response of volcanoes to earthquakes at a global, regional and local scale using remote sensing to (1) examine the strength of the relationship at varying scales, (2) identify parameters that influence volcanic activity triggering following an earthquake and (3) test the ability of earthquakes as a precursory indicator to volcanic activity. These aims will be met by the following objectives:

- To provide an evaluation of previous earthquake-volcano interactions by conducting a comprehensive review of literature;
- To detect the timing and magnitude of changes in volcanic activity before and after seismic events using remotely sensed data;
- To test the consistency of the relationship at varying spatial scales including examining patterns at a global, regional and local scale;
- To identify the parameters which control a response through the assessment of case-specific earthquake-volcano interactions;
- To incorporate seismic and volcanic variables to define a model for the prediction of volcanic activity following seismic events and evaluate its utility using earthquake-volcano interaction case studies;
- To identify a range of common factors which contribute towards the relationship between earthquakes and volcanoes and explain these with physical mechanisms of response.

By conducting a systematic review of earthquake-volcano interactions and identifying response criteria to detect the timing and magnitude of changes in volcanic activity following an earthquake, this thesis will develop and outline a standardised method to identify earthquake-volcano interactions that will be used in this research as well as informing future assessments of the relationship. Furthermore, the focus of this research to identify the parameters that influence the response of volcanoes to earthquakes will enable a volcano's likelihood for response in future instances of earthquake-volcano interactions to be assessed and proposed mechanisms of response to be evaluated. This has the potential to provide valuable insights into the interactions between earthquakes and volcanoes which will aid the understanding of the processes that trigger volcanic activity following earthquakes. Finally, the conditions that increase a volcano's probability for response will be suggested and the processes that lead to seismically triggered unrest proposed. If determined, this research will provide a valuable contribution to knowledge by determining the criteria to identify potentially triggered activity, recognise the factors that influence a volcano's response and establish the state of the relationship to identify the potential use of earthquakes as a precursory indicator to volcanic activity.

1-4 THESIS STRUCTURE

This chapter has provided a brief introduction into the study of earthquake-volcano interactions as well as outlining the advantages of satellite remote sensing for volcanic activity monitoring and the aims and objectives of this thesis. The following chapter will now provide a more detailed interrogation of the relationship between earthquakes and volcanoes, outline previous attempts to forecast volcanic activity and set out the principles of thermal remote sensing. Chapter 3 will then detail the data sources and methods used in this thesis in the assessment of volcanic activity triggering following large magnitude earthquakes. Due to the nature of this research to examine any relationship at varying spatial scales, the results will be divided. Chapter 4 will present and discuss the results of global volcanic radiant flux responses to earthquakes and Chapter 5 will provide an examination of case-specific earthquake-volcano interactions as well as assessing the ability to predict a volcano's response. Chapter 6 will then evaluate the most likely mechanism(s) for response and propose a process of response and, finally, Chapter 7 will conclude by summarising the main findings and implications of this thesis as well as evaluating this research and identifying future research opportunities.

CHAPTER 2

LITERATURE REVIEW

The importance of understanding precursors to natural hazards and providing adequate forecasts was outlined in Chapter 1 as well as the advantages of remote sensing for volcanic activity monitoring. This chapter will interrogate earthquake-volcano interactions literature, with particular focus on methodological approaches to identify the characteristics of triggered responses. Firstly, the principles of volcanic eruption forecasting and modelling will be examined. Based on this, volcanic activity triggers will be outlined and the current state of understanding of interactions between earthquakes and volcanic activity will be reviewed as well as key mechanisms that have been suggested to control a response. The application of remote sensing in volcano monitoring will then be explored and the technical aspects of thermal remote sensing used in this thesis will be detailed. Lastly, this review will be summarised identifying key challenges faced by previous research as well as informing the focus of this thesis.

2-1 MODELLING AND FORECASTING VOLCANIC ACTIVITY

The forecasting and prediction of volcanic eruptions has remained a primary goal of volcanology for a number of decades (UNESCO 1972; Voight and Cornelius 1991; Scarpa 2001; Sparks 2003; Sparks and Aspinall 2004; Marzocchi and Bebbington 2012; Salvage and Neuberg 2013). Previous attempts to forecast volcanic activity have focussed on the ability to estimate future eruptions and issue effective warnings (UNESCO 1972; Rymer and Williams-Jones 2000; Scarpa 2001; Sparks and Aspinall 2004; Marzocchi and Bebbington 2012). In this way, the fact that volcanoes are intrinsically unpredictable (Sparks and Aspinall 2004), has meant that the identification of precursors, knowledge of uncertainties within a system, patterns of activity and thresholds for response have particular utility in eruption forecasting (McNutt 2002; Sparks 2003; Huppert and Sparks 2006; De La Cruz-Reyna and Tilling 2008; Selva *et al*. 2012).

Considering these factors, perhaps the most critical precursory indicator to identify changes in activity and indicate impending eruptions is volcanic seismicity (Tokarev 1971; Chouet 1996; McNutt 1996; Jaquet and Carniel 2001; McNutt 2002; Collombet *et al*.

2003; Gerst 2004; Tárraga *et al*. 2006; Brenguier *et al*. 2008; Marzocchi and Bebbington 2012; Power *et al*. 2012; Salvage and Neuberg 2013). Indeed, McNutt (2002) stated that the majority of volcanic eruptions are preceded by a seismic precursor with changes in seismicity being used to forecast eruptions at Kilauea, Hawai'i (Chastin and Main 2003), Piton De La Fournaise, Réunion (Brenguier *et al*. 2008), Redoubt, Alaska (Chouet 1996) and Soufrière Hills, Montserrat (Kilburn and Voight 1998).

Another precursory phenomenon identified as being critical in volcanic hazard forecasting is the role of stress and material failure (Voight 1988; Kilburn 2003; Sparks 2003; Gerst 2004). Although closely related to volcanic seismicity and deformation (Kilburn 2003; Kilburn and Sammonds 2005), the theory of fracturing in which cracks are stable until a large enough stress (causing fracturing and connecting magma to the surface) is exerted forms the basis for a material failure forecast model which has forecasting capabilities up to days (Voight and Cornelius 1991; Kilburn and Voight 1998; Kilburn 2003; Kilburn and Sammonds 2005). However, considering the potential range of precursory indicators, any attempts to forecast future activity must first establish the factors influencing unrest before determining their level of significance.

Uncertainties within a volcanic system are also another factor that must be accounted for (Sparks 2003; Sparks and Aspinall 2004; Marzocchi and Bebbington 2012; Power *et al*. 2012; Selva *et al*. 2012). Perhaps the main issue when attempting to forecast future eruptions is the range of triggers that may influence periods of unrest (Connor *et al*. 2003; Sparks 2003; Brenguier *et al*. 2008). Therefore, in order to provide accurate forecasts, volcanic processes need to be clearly understood so that future activity can be accurately modelled and forecast (Chouet 1996; Brenguier *et al*. 2008). Probabilistic forecasting, which provides operational forecasts based on the likelihood of activity and accounting for complex volcanic processes and uncertainties, therefore, offers particular utility for volcanic eruption modelling (Decker 1986; Connor *et al*. 2003; Sparks 2003; Sparks and Aspinall 2004; Jaquet *et al*. 2006; Marzocchi and Bebbington 2012; Selva *et al*. 2012; Cañón-Tapia 2014).

Another factor identified as critical in eruption forecasting is the ability to recognise changes in behaviour that may indicate impending activity or a period of unrest (McNutt 2002; Gerst 2004; Brenguier *et al*. 2008; Power *et al*. 2012). The high variability of volcanoes means that an understanding of their long-term behaviour and individual characteristics need to be considered to accurately infer changes from their 'normal' state (UNESCO 1972; Decker 1986; McNutt 1996; McNutt 2002; Sparks and Aspinall 2004; Brenguier *et al*. 2008). In addition, in the same way that an individual volcano's behaviour is thought to influence activity, the identification of thresholds for response are key to eruption forecasting (Connor *et al*. 2003; Power *et al*. 2012; Selva *et al*. 2012). The existence of a triggering threshold and difficulties distinguishing between periods of unrest and an impending eruption means that it is hard to predict the scale, duration and timing of an eruption even if there are precursory signals (Huppert and Sparks 2006). Therefore, a volcano's repose, or time since last eruption, may be more indicative of eruption probability (Wickmann 1966).

Although no criteria exist for forecasting volcanic activity, recommended methods for prediction include multiple volcanic datasets, statistical analyses and eruption modelling (Kilburn and Voight 1998; Sparks 2003; Sparks and Aspinall 2004; Kilburn and Sammonds 2005; Selva *et al*. 2012; Salvage and Neuberg 2013). Connor *et al*. (2003), for example, demonstrated the importance of examining all possible scenarios by using a log logistic probability distribution model to account for differing conduit processes during explosions at Soufrière Hills, Montserrat. Selva *et al*. (2012), in comparison, recommended the use of a Bayesian event tree scheme where the probability of the model is updated by incorporating parameters of varying importance, first, as conceptual models and, finally, as a probabilistic forecast model. In terms of statistical analyses, a number of studies including Jaquet *et al*. (2006) and Salvage and Neuberg (2013) recognise the need to identify patterns of activity to aid forecasting.

One such approach that identifies patterns within large and complex datasets is machine learning. Machine learning (also termed data mining, artificial intelligence or deep learning) uses computer programming and statistical methods to automatically detect patterns within a dataset (Alpaydin 2010; Murphy 2012; Jones 2014). Originating from the idea of neural networks within a human brain, a computer can learn from data that can then be used to make predictions and other decisions (Murphy 2012; Jones 2014). Examples of the use of machine learning include web page ranking and facial recognition (Figure 2-1) as well as many applications in geosciences (e.g. land surface analysis, vegetation indices, landslide hazard assessment and atmospheric dispersion models) (Cervone *et al*. 2008; Smola and Vishwanathan 2008; Waske *et al*. 2009; Lary 2010; Samui and Sitharam 2011; Jones 2014).

FIGURE 2-1 THE USE OF NEURAL NETWORKS TO IDENTIFY HUMAN FACES (SOURCE: JONES 2014: 148).

There are two main types of machine learning (supervised and unsupervised) that use statistical methods such as support vector machines, neural networks, random forests and CART (classification and regression) decision trees to obtain valuable information from data which is often too large for standard statistical techniques (Breiman *et al*. 1984; Waske *et al*. 2009; Alpaydin 2010; Lary 2010; Samui and Sitharam 2011). CART decision trees, in particular, enable both categorical (classification) and numerical (regression) data to be modelled by learning from the inputs, *x,* and outputs, *y,* given, *D*, the number of pairs and an associated number of attributes (Alpaydin 2010; Murphy 2012):

$$— \qquad \text{Eq. 2-1}$$

The multivariate, non-parametric aspect of CART decision trees means that the number of nodes grows with the data, providing the most accurate predictive model (Murphy 2012; BigML 2015). Therefore, on the basis of the proposed relationship between earthquakes and volcanoes, machine learning may be an appropriate platform to analyse the parameters that affect the relationship between earthquakes and volcanic activity.

Overall, the identification of precursors, or triggers, has a number of important implications for eruption monitoring and forecasting. Therefore, considering the factors explored in this section of the review, it is clear that the design and implementation of a volcanic forecast model would need to incorporate an assessment of triggers for reliable forecasting. In addition, patterns during previous instances of unrest would first need to be identified and conceptual models developed in order to assess the use of any precursory indicator to volcanic activity.

2-2 VOLCANIC ACTIVITY TRIGGERING

Volcanic eruptions result from a complex set of interactions and understanding how and why a volcano erupts is important to be able to interpret volcanic activity triggers and forecast the future probability of activity. In recent years, it has been increasingly recognised that a volcano's magmatic system is critical in this process and that there are a number of factors that can influence this state of equilibrium and trigger an eruption. The range of potential triggers, in particular, are diverse and include processes such as volatile exsolution, magma injection, thermal expansion, ice unloading and interactions with water (Sparks 1981; Blake 1984; Neuberg 2000; Matthews *et al*. 2002; Cañón-Tapia 2014). Broadly, these factors can be classified into two main categories 1) internal processes related to conditions in and around the magma chamber and 2) external processes that may influence the pressure and conditions of the volcanic system (Schmincke 2004; Lockwood and Hazlett 2010; Cañón-Tapia 2014).

In all cases, a change in the internal pressure of the magmatic system is required to create instability and initiate an eruption. Internally, the addition of new magma, volatile exsolution and thermal expansion can all increase the pressure inside the magma chamber (Cañón-Tapia 2014). The injection of new magma into a system, in particular, has been shown to be capable of initiating pressure changes that lead to an eruption (Cañón-Tapia 2014). Increases in magma flux due to this process occur when the rate of melting increases and new magma is injected into the system (Cañón-Tapia 2014). These variations in magma supply increase the overall volume of material in a magma chamber and have been attributed to changes in activity at Kilauea, Hawai'i as well as new eruptions (Poland *et al*. 2012; Cañón-Tapia 2014). In addition, it has been argued that in situations where the new influx of magma is inherently different to the current composition that this can also act as a trigger to volcanic eruptions (e.g. Sparks and Sigurdsson 1977; Murphy *et al*. 1998). In these cases, rapid heating from magma mixing have been shown to be capable of causing explosive eruptions.

Alongside this, volatile exsolution involves the separation of dissolved gases from the magma forming gas bubbles (Parfitt and Wilson 2008; Cañón-Tapia 2014). This process of vesiculation can result from a sudden decrease in pressure, change in temperature, formation of crystals (i.e. second boiling) or magma injection and, once again, results in overpressure (Pyle and Pyle 1995; Parfitt and Wilson 2008; Cañón-Tapia 2014). Finally, an increase in the temperature of the magma chamber can result in thermal expansion and cause an eruption due to an increase in the overall pressure of the system (Cañón-Tapia 2014).

Similarly, external triggers may also result in explosive volcanic eruptions. One such example of these external processes are changes in the pressure above a magma chamber. Processes such as ice unloading, sea level change or volcano-sector collapse all have the potential to decrease the pressure on a magma chamber as a result of decreasing the load (Voight *et al*. 2002; Sigmundsson *et al*. 2010; Cañón-Tapia 2014). This decrease in pressure affects the equilibrium within the magma chamber initiating decompression and leading to an eruption (Cañón-Tapia 2014).

The interaction of magma with water is another phenomenon that has attracted considerable interest (Parfitt and Wilson 2008). There are a variety of processes related to the interaction with water, for example, volatiles within a magma chamber interact with external water bodies resulting in rapid vaporisation or an already rising magma body may encounter ground or surface water causing heat exchange (Cañón-Tapia 2014). While each of these processes may not directly increase the pressure of the system, it is the interactions with the magma body that initiates processes leading to overpressure or hydromagmatic eruptions (Parfitt and Wilson 2008).

Finally, and of particular interest to this thesis, the interaction of volcanoes with large magnitude earthquakes has the potential to trigger volcanic eruptions and unrest (Linde and Sack 1998; Hill *et al*. 2002; Eggert and Walter 2009). The processes related to this trigger are suggested to result in changes in stress around the magma chamber or induce physical changes in the magma system initiating processes of unrest (Brodsky *et al*. 1998; Walter *et al*. 2007; Eggert and Walter 2009; Bebbington and Marzocchi 2011). This relationship and the potential triggering mechanisms will be further discussed in Section 2-3.

2-3 THE RELATIONSHIP BETWEEN EARTHQUAKES AND VOLCANIC ACTIVITY

The potential relationship between earthquakes and volcanoes has serious implications for the identification of precursors, hazard assessment and early warning (Walter and Amelung 2004; Walter *et al*. 2007; Fattori Speranza and Carniel 2008; Alam *et al*. 2010). Spatially, early recognitions of a link between these hazards resulted from their locations along subducting plate boundaries. More recently the temporal link between earthquakes and volcanic activity has attracted considerable interest and it has been identified that since 1950 all large earthquakes have been followed by volcanic eruptions in the following year: 1952 Kamchatka M9.2, 1960 Chile M9.5, 1964 Alaska M9.2, 2004 (2005) Sumatra-Andaman M9.3 (M8.7) and 2011 Japan M9.0 (Walter and Amelung 2007; Watt *et al*. 2009; Wang *et al*. 2011). This section will establish the current state of understanding of the relationship between earthquakes and volcanoes. In this respect, the origins of earthquake-volcano interactions research will first be outlined; key methods and a review of previous research that identified conditions that influence a volcano's response will then be discussed. The key challenges facing earthquake-volcano investigations will be detailed along with an overview of the use of satellite remote sensing to assess any relationship and, finally, a review of proposed mechanisms will be provided.

2-3-1 ORIGINS OF EARTHQUAKE-VOLCANO RESEARCH

Within academic literature there are few cases of explosive volcanic eruptions following large earthquakes. Indeed, occurrences of increased volcanic seismicity and unrest (thermal activity, deformation and degassing) are more commonly noted with historic observations over the past 180 years indicating instances of increased volcanic activity following large tectonic earthquakes (Darwin 1840; Rockstroh 1903; Hédervári 1979; Zobin *et al*. 1983; Newhall and Dzurisin 1988). Perhaps one of the earliest examples of increased volcanic activity following an earthquake was documented by Darwin (1840) who provided a detailed summary of unusual volcanic activity at four volcanoes following the 1835 Concepción (M8.5) earthquake. With responses lasting several months, Darwin (1840:605) suggested that these events *"were part of one and the same great phenomenon"* which were likely to exist in other regions around the world or at a global scale. Based on these responses, Darwin (1840) alluded that certain conditions need to be met for a response to occur with a number of possible mechanisms controlling the relationship. Crucially, however, Darwin (1840) acknowledged the uncertainty in these observations stating that the use of secondary accounts is subjective due to the heightened awareness (to natural hazards) or selective memories of his sources.

Building on this early work, a number of studies indicated that, in addition to a number of conditions controlling the relationship, a volcano must be in a critical state (i.e. magma present) for a response to occur (Nakamura 1971; Yamashina and Nakamura 1978). The response of volcanoes located within an earthquake's rupture zone or on the landward side of an earthquake's epicentre, for example, demonstrate the crucial role that regional characteristics and stress changes have on the relationship between volcanic and seismic activity (MacGregor 1949; Blot 1965; Latter 1971; Nakamura 1971; Yokoyama 1971; Nakamura 1975; Kimura 1976; Carr 1977; Nakamura 1977; Yamashina and Nakamura 1978; Acharya 1982a; Acharya 1982b; Acharya 1987; Rikitake and Sato 1989). In particular, Acharya (1987) suggested that volcanoes within an earthquake's rupture zone are subjected to the maximum energy released by an earthquakes and are, therefore, more likely to respond. Further examples of a complex coupling between earthquakes and volcanoes include the absence of volcanic activity within the vicinity of a great earthquake's epicentre, a volcano's location within the arc setting, the response of volcanoes that are adjacent to one another and localised areas of increased volcanic activity (Acharya 1982b; Acharya 1987).

In order to explore the forecasting potential of any relationship, a number of studies examined the use of earthquakes as a precursory indicator to volcanic activity (MacGregor 1949; Furumoto 1957; Carr 1977; Yokoyama and De la Cruz-Reyna 1990). By analysing spatial and temporal responses of volcanoes to earthquakes, regional patterns of unrest were identified showing the potential for forecasting based on local scale (i.e. within the same geographic region) interactions. Most notably, Hill *et al*. (1985) demonstrated the co-occurrence of earthquakes and eruptions in Long Valley Caldera, California. The prediction of a major tectonic earthquake strongly influencing volcanic activity in this region (Hill *et al*. 1985) was later confirmed when a M7.3 earthquake (1992 Landers, California) resulted in the most widely documented instances of triggered seismicity in volcanic and geothermal areas across the Western United States (Hill *et al*. 2002; West *et al*. 2005).

Reports of triggered volcanic activity in Hawai'i, Greece, Italy and the Aleutian Arc have also resulted in suggestions of a two-way coupling between earthquakes and volcanoes

(Tilling *et al*. 1976; Sharp *et al*. 1981; Papadopoulos 1986; McNutt 1987; Marzocchi *et al*. 1993). Carr (1977), in particular, suggested that based on a two-way coupling between large earthquakes and volcanic activity, stress changes following a period of volcanic unrest were equally capable of inducing regional seismicity. As a result, it may be possible to predict tectonic earthquakes based on changes in volcanic activity, a theory tested by Acharya (1981).

Further examinations of this potential volcano-earthquake relationship recognised a pattern in which a complex sequence of volcanic activity preceded large earthquakes (Berg and Sutton 1974; Kimura 1976; Carr 1977; Acharya 1982a; Acharya 1982b; Acharya 1987; Thatcher and Savage 1982). In these cases, precursory volcanic activity is noted up to a decade before an earthquake, followed by a period of volcanic silence and, finally, an increase in volcanism near (before or after) the time of the earthquake (Carr 1977; Acharya 1982a; Acharya 1987). The second period of increased volcanic activity is highly variable once again indicating that a number of conditions must exist that influence any relationship between earthquakes and volcanoes (Carr 1977). In contrast to the findings of Latter (1971), however, Carr (1977), Acharya (1982a; 1982b) and Yokoyama and De la Cruz-Reyna (1990) find a relationship between the magnitude of earthquake and time of eruption. Carr (1977) and Acharya (1982a; 1982b) also suggested that large (M≥8.0) earthquakes are preceded by periods of volcanic activity up to 15 years before an event. As such, it is clear that a review of the characteristics of the triggering earthquake and the responding volcano is essential to identify the temporal and spatial dynamics of the relationship and infer the principles and mechanisms of earthquake-volcano interactions.

2-3-2 METHODS TO ASSESS EARTHQUAKE-VOLCANO INTERACTIONS

The first attempts at a statistical and global study were conducted by Linde and Sacks (1998). Motivated by the triggered seismicity at Long Valley Caldera, California following the 1992 Landers earthquake, Linde and Sacks (1998) examined historical records dating back to the 18th Century to assess whether there was an increase in volcanic eruptions following large earthquakes (M≥7.0) up to 750 km away. Overall, this work showed that there were significantly more eruptions on days of large earthquakes than expected by chance. In addition, this work suggested that volcanoes in a critical state (i.e. magma present) may be more susceptible to triggering following the passage of seismic waves. This is because a volcano would already be in a state ready to erupt and the stress changes following the earthquake advanced the onset of an eruption. Nevertheless, the use of historical records rather than instrumental measurements hindered the reliability of the results produced (further discussed in Section 2-3-5, pg. 29).

By emphasising the importance of comparing volcanic activity before and after an earthquake to positively identify a response, Linde and Sacks (1998) set out a key method that has been replicated in the majority of subsequent studies investigating the relationship at a regional and global scale (examples include: Richter *et al*. 2004; Manga and Brodsky 2006; Cigolini *et al*. 2007; Lemarchand and Grasso 2007; Eggert and Walter 2009; Watt *et al*. 2009; Delle Donne *et al*. 2010). Subsequent studies have since updated and re-produced this method or, alternatively, modified factors such as data type, criteria for analysis and the type of analysis conducted, Figure 2-2. In Lemarchand and Grasso (2007), for example, an updated volcanic and seismic dataset (1973-2005) was used to assess the spatial and temporal parameters of the relationship. Richter *et al*. (2004) and Cigolini *et al*. (2007), in comparison, took advantage of the availability of instrumental data, fumarole temperature and radon degassing, respectively, to assess the response of two volcanoes to regional earthquakes.

FIGURE 2-2 EARTHQUAKE-VOLCANO INTERACTIONS AT MERAPI, INDONESIA IDENTIFIED BY COMPARING TEMPERATURE AND PYROCLASTIC AVALANCHES BEFORE AND AFTER TWO M6.3 EARTHQUAKES (SOURCE: WALTER *ET AL*. 2007: 2).

In an attempt to assess if earthquakes could increase the probability of volcanic unrest, Marzocchi (2002) examined the statistical significance of earthquake-volcano couplings. Overall, this study revealed that there is a significant correlation between earthquakes and volcanoes 0-5 (5/8 cases) and 30-35 (2/4 cases) years after an event up to 1,000 km away. Indeed, this strong temporal relationship presents a key parameter now identified to affect the triggering of volcanic activity. The challenge faced by researchers, however, is the ability to quantify an appropriate temporal delay in which volcanoes may respond. For example, Eggert and Walter (2009) suggest delayed responses of up to 10 years for changes in the magma chamber to manifest in an eruption whereas Hill *et al*. (1993; 1995); Husen *et al*. (2004a) and Prejean *et al*. (2004) identify immediate responses (e.g. minutes to days) following the passage of seismic waves in North America. In this context it is suggested that delayed responses result from the complex interactions (i.e. those processes initiating unrest following an earthquake) and changes in stress following an earthquake (Linde *et al*. 1994; Walter and Amelung 2007; Watt *et al*. 2009; Wang *et al*. 2011), a factor which is still not clearly understood.

In Marzocchi *et al*. (2002) and Marzocchi *et al*. (2004) the role of stress diffusion surmised by Marzocchi (2002) is considered and assessed. Modelling the global effects of an earthquake on stress diffusion, Marzocchi *et al*. (2002) found that volcanoes within the zones of largest stress change are more susceptible to triggering. In particular, Marzocchi *et al*. (2002) stated that the elastic response of the lithosphere and the viscoelastic relaxation of the crust are evidence of stress diffusion following an earthquake, concluding that the influence of large earthquakes on regional stresses is a key mechanism in volcanic activity triggering. In addition, Marzocchi *et al*. (2004) suggested that changes in stress resulting from the passage of seismic waves can result in the re-activation of volcanoes as well as trigger volcanoes up to 1,000 km from an earthquake's epicentre, Figure 2-3.

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FIGURE 2-3 DISTANCES BETWEEN TRIGGERING EARTHQUAKE AND RESPONDING VOLCANO (SOURCE: MARZOCCHI *ET AL*. 2004: 3).

2-3-3 FACTORS INFLUENCING EARTHQUAKE-VOLCANO INTERACTIONS

With a view to explore the processes that trigger volcanic eruptions and unrest, Hill *et al*. (2002) provided a review of the emerging evidence for earthquake-volcano interactions. One key parameter identified to be gaining emphasis within this field is the state of the volcanic system (Hill *et al*. 1995; Linde and Sacks 1998; Hill *et al*. 2002; Marzocchi *et al*. 2002). It is suggested that if a volcano is in a state ready to erupt (i.e. magma present and conditions right for an eruption), earthquakes may be capable of enhancing the onset of an eruption resulting in premature activity (Brodsky *et al*. 1998; Linde and Sacks 1998; Cannata *et al*. 2010; Bebbington and Marzocchi 2011; Marzocchi and Bebbington 2012; Prejean and Haney 2014). Therefore depending on the sensitivity of the system, volcanoes may be susceptible to subtle changes in stress (Hill *et al*. 1993; Hill *et al*. 2002; Walter and Amelung 2006). Importantly, more recent assessments have also identified the state of the volcanic system as a key parameter controlling a response (Walter *et al*. 2007; Eggert and Walter 2009; Dzierma and Wehrmann 2010). In particular, volcanoes with long periods of quiescence (i.e. latent activity) are identified as more susceptible to triggering (Walter and Amelung 2007; Eggert and Walter 2009). Furthermore, it is suggested that the selective responses of volcanoes is due (in part) to the state of the volcanic system where a volcano's readiness to erupt determines whether a response is observed (Hill *et al*. 1995; Husen *et al*. 2004b; Prejean *et al*. 2004; De la Cruz-Reyna *et al*. 2010). In a further review, Manga and Brodsky (2006) noted that the relationship also varied at a spatial and temporal scale, indicating a tendency for the same volcanoes to respond, a finding also recognised by Hill-Butler (2012).

Continuing with this theme, Eggert and Walter (2009) provide evidence for a statistically significant relationship between the two-way coupling of earthquakes and volcanoes. As noted by Nostro *et al*. (1998), changes in stress resulting from the movement of magma may cause instability triggering an earthquake and, equally, a change in stress (resulting from an earthquake) may initiate an eruption by elastic stress transfer. Indeed, instances of volcano-earthquake triggering have been noted in Hawai'i (Walter and Amelung 2004), Italy (Gresta *et al*. 2005), Japan, Figure 2-4 (Kimura 1976; Alam *et al*. 2010), New Zealand (Villamor *et al*. 2011) and at a global scale (Lemarchand and Grasso 2007). It would be possible, therefore, for a two-way coupling to exist whereby a set of complex interactions (i.e. processes of change following an event capable of initiating new seismic or volcanic activity) causes earthquakes and volcanic activity to result from each other, Figure 2-5 (Kimura 1976; Nostro *et al*. 1998; Feigl *et al*. 2000; Nishimura *et al*. 2001; Gudmundsson and Brenner 2003; Walter and Amelung 2006; Walter 2007).

FIGURE 2-4 RELATIONSHIP BETWEEN ERUPTIONS (CIRCLE) AND LARGE EARTHQUAKES (VERTICAL BAR) IN THE SAGAMI TROUGH, JAPAN (SOURCE: ALAM *ET AL*. 2010: 3).

FIGURE 2-5 CYCLE OF EARTHQUAKE-VOLCANO INTERACTIONS AT MAUNA LOA, HAWAI'I (SOURCE: WALTER AND AMELUNG 2006: 15).

Based on these suggestions, a number of studies have attempted to quantify the influence of stress changes on any relationship between earthquakes and volcanoes (Feigl *et al*. 2000; Selva *et al*. 2004; West *et al*. 2005; Chen *et al*. 2009; Wang *et al*. 2011; Kriswati *et al*. 2013; Lupi *et al*. 2014; Bonali *et al*. 2015). Using data from the associated earthquake, Selva *et al*. (2004), West *et al*. (2005) and Walter *et al*. (2007) modelled stress changes to assess the causal relationship between earthquakes and volcanoes. In these cases, increases in the stress field were found to correlate with triggered responses (seismicity, increased fumarole temperatures and increased magma extrusion) at volcanoes (Figure 2-6 & 2-7).

More recently, Wang *et al*. (2011) detailed a method to calculate changes in the stress field of Shinmoedake following the 2011 M9.0 Japan earthquake. Overall, these results showed that 3 volcanoes, including Shinmoedake, were located in areas of volumetric expansion and that increases in activity were expected as a result of unclamping and magma ascent. As a result, by examining the changes in stress resulting from an earthquake it may be possible to identify volcanoes that may be triggered.

Figure 2-6 Changes in stress beneath Merapi, Indonesia following a M6.3 strike-slip earthquake, red indicates areas where the fault slip is encouraged (Source: Walter *et al*. 2007: 3).

Figure 2-7 Modelled stress changes following the 2002 Denali fault earthquake, Alaska; red-yellow indicates positive stress changes, blue-green indicates negative stress changes (Source: Selva *et al*. 2004: 386).

Globally, it is clear that the relationship between earthquakes and volcanoes is made up of complex set of interactions (i.e. processes capable of initiating unrest) resulting in significantly more eruptions being recorded in the years following an earthquake (Walter and Amelung 2007; Eggert and Walter 2009, Battaglia *et al*. 2012). More localised assessments, however, highlight a disparity between the number of recorded interactions. Within South America, for example, earthquake-volcano interactions have a long history of observation and research (Darwin 1840; Berg and Sutton 1974; Acharya 1987; Barrientos 1994; Watt *et al*. 2009), whereas in Japan, there are significantly fewer reports of triggering falsely suggesting that this area is less responsive (Harrington and Brodsky 2006). With this in mind, research has emphasised that certain sub-regions (Figure 2-8), particularly volcanic arcs located within the Pacific Ring of Fire, may be more susceptible to triggering (Marzocchi 2002; Eggert and Walter 2009). To gauge the spatial extent of this relationship, earthquake-volcano assessments are therefore required at sub-regional and global scales.

Prior to the 1992 M7.3 Landers earthquake, California, cases of triggering were constrained by intermittent records and the limited availability of instrumental data. This unique event enabled researchers to obtain instrumental data of widespread triggering across the Western United States (Hill *et al*. 1993; Linde *et al*. 1994; Hill *et al*. 1995; Johnston *et al*. 1995; Sturtevant *et al*. 1996). Most notably, this was the first event where periods of unrest were recorded at a regional scale and, in addition, demonstrated that periods of unrest (volcanic seismicity, deformation, geyser activity and degassing) as well as eruptions can be triggered following an earthquake (Hill *et al*. 1993; Hill *et al*. 1995; Johnston *et al*. 1995; Sturtevant *et al*. 1996). In fact, further cases of triggering following the 1999 M7.1 Hector Mine earthquake, California, the 2002 M7.9 Denali Fault earthquake, Alaska, and other large magnitude events (M≥7.0) showed that cases of triggered seismicity were most common following an earthquake (Gomberg *et al*. 2001; Husen *et al*. 2004a; Moran *et al*. 2004; Selva *et al*. 2004; Brodsky and Prejean 2005; Battaglia *et al*. 2012).

FIGURE 2-8 CORRELATION CO-EFFICIENTS OF EARTHQUAKE-VOLCANO INTERACTIONS IN DIFFERENT SUB-REGIONS (SOURCE: EGGERT AND WALTER 2009: 10).

It is well known that local volcanic seismicity is an important precursor to volcanic unrest. More recent assessments of volcanic seismicity prior to eruptions, however, have identified subtle changes in their characteristics (Zobin and Levina 1998; Roman *et al*. 2006; Roman and Heron 2007; Roman and Gardine 2013). In particular, magma pressurisation and ascent are detected alongside changes in fault plane solutions identifying a valuable precursor prior to the onset of activity, Figure 2-9 (Roman *et al*. 2006; Roman and Heron 2007; Roman and Gardine 2013). Similarly, Pollitz *et al*. (2012) noted a change in aftershock patterns following a M8.6 strike slip event (Indian Ocean, 2012) as compared to other thrust events in the same region. Investigations of earthquake-volcano interactions should, therefore, conduct an assessment of earthquake fault plane solutions to examine the influence that earthquake characteristics may have on triggering.

FIGURE 2-9 CHANGE IN FAULT PLANE SOLUTIONS DURING PERIODS OF UNREST AT SOUFRIÈRE HILLS, MONTSERRAT. GREY ARROW INDICATES AZIMUTH OF INFERRED REGIONAL COMPRESSION (SOURCE: ROMAN *ET AL*. 2006: 247).

The increasing availability of instrumental data has also identified a number of key findings that provide clues about the relationship. Firstly, it must be noted that despite widespread triggering following each of these earthquakes, not all volcanic sites respond (Hill *et al*. 1993; Johnston *et al*. 1995; Sánchez and McNutt 2004; Brodsky and Prejean 2005; Bebbington and Marzocchi 2011). In this regard, it must be remembered that volcanoes may be affected by a number of other factors that influence unrest and it is suggested that a number of conditions may exist for a volcano to respond (Hill *et al*. 1993; Johnston *et al*. 1995). Comparably, earthquake-volcano interactions in Indonesia, Italy, Japan and South America have recognised similar selectivity supporting the theory for favourable conditions (Lara *et al*. 2004; Harrington and Brodsky 2006; Walter *et al*. 2009; Watt *et al*. 2009; Bebbington and Marzocchi 2011). At the same time, it has been noted that more than one volcano is likely to respond. Indeed, observations of earthquake-volcano interactions in South America show that, on average, 3-4 eruptions are triggered following an earthquake (Watt *et al*. 2009). The processes relating to this, however, are complex and it is equally likely that following the triggering of one period of unrest, subsequent volcanoes are triggered as a result of the changes in pressure due to the initial activity as suggested by Zobin and Levina (1998).

2-3-4 EXAMPLES OF EARTHQUAKE-VOLCANO INTERACTIONS

In terms of triggering, individual volcanoes are also found to exhibit varying levels of response. As discussed in Section 2-3-3 (pg. 18), a number of volcanoes are known to have responded to more than one earthquake trigger whilst other volcanic sites do not have any known cases of triggering (Prejean *et al*. 2004). One such example was the varying levels of response (regionally and globally) reported following the 2004 Boxing Day earthquake, Indonesia. This event, in particular, highlighted the importance of developing reliable measures of a volcano's response following an earthquake. Harris and Ripepe (2007), for example, state that there were no triggered responses (regional or global) following the M9.1 event, whereas, West *et al*. (2005) identified triggered seismicity at Mount Wrangell, Alaska 11,000 km away. Interestingly, Manga and Brodsky (2006) suggested that a later M8.6 earthquake (Sumatra, March 2005) induced triggered activity at 3 volcanoes (including Barren Island, Indonesia a volcano that had been dormant for more than a decade). A later study by Walter and Amelung (2007), however, inferred that the M9.1 earthquake initiated a sequence of events, including the March 2005 earthquake that culminated in the eruption of Barren Island, Indonesia and triggered seismicity at other volcanic centres.

Globally, periods of volcanic unrest following the 2004 M9.1 event were observed up to 17,000 km away (Delle Donne *et al*. 2010), with triggered seismicity at Mauna Loa, Hawai'i (Okubo and Wolfe 2008), Kyushu, Japan (Harrington and Brodsky 2006) and Mount Wrangell, Alaska (West *et al*. 2005). Mount Wrangell, in particular, presents an interesting case demonstrating the potential for large earthquakes to affect volcanic systems at a global scale (West *et al*. 2005). Recognising changes in seismicity following the passage of seismic waves, West *et al*. (2005) associated these instances of change with periods of deformation suggesting that small changes in displacement caused shear failure. In contrast, a M8.1 earthquake 3 days before the Boxing Day event did not trigger a response while the 2002 Denali Fault earthquake (M7.9) saw a decrease in seismicity by up to 50% (West *et al*. 2005). Consequently, research is required to identify the favourable conditions that control whether a volcano responds, a factor that will be considered and assessed during this research.

Following the 2004 Boxing Day earthquake it was also noted that seismicity within the volcanic arc was altered with the number of M≥4.5 earthquakes decreasing for up to 5 years (Sevilgen *et al*. 2012). Despite this, earthquake-volcano assessments in this region have been able to identify that vicinity to earthquake rupture zone (or zone of maximum stress change) has a larger influence than distance to earthquake epicentre (Walter and Amelung 2007; Takada and Fukushima 2013). By examining stress changes following an earthquake, Walter and Amelung (2007) found that all responding volcanoes were located in areas of permanent stress change (static stress). What is more, similar findings of earthquake-earthquake triggering suggest that the rupture zone is affected by the magnitude of the triggering earthquake (Helmsetter 2003). Therefore, in the same way that Wells and Coppersmith (1994) identified the possibility of estimating the location and magnitude of future earthquakes, it may be possible to identify volcanoes that may be triggered based on earthquake characteristics (magnitude, rupture length, rupture area and displacement).

For volcanoes within Central and South America, similar findings support the argument that a number of conditions need to be met for volcanic activity to be triggered (Barrientos 1994; Lara *et al*. 2004; Dzierma and Wehrmann 2010; Tárraga *et al*. 2012). Most commonly, triggering is recognised to result in an increase in eruptive activity following the passage of seismic waves whether it is a new eruption or a modification in activity at a volcano with on-going unrest (Watt *et al*. 2009; De la Cruz-Reyna *et al*. 2010). Selective triggering following the 2010 M8.8 Chile earthquake, however, demonstrated the uncertainty in determining any relationship (Bonali *et al*. 2012; Lupi *et al*. 2012; Mora-Stock *et al*. 2012; Bonali 2013; Bonali *et al*. 2013; Pritchard *et al*. 2013; Farías *et al*. 2014; Pritchard *et al*. 2014).

Both Mora-Stock *et al*. (2012) and Bonali *et al*. (2013) indicated that the differing responses of volcanoes to earthquakes demonstrates that a number of parameters must influence the relationship and understanding these factors is critical to aid prediction. In particular, Bonali *et al*. (2013) surmised that changes in stress are capable of promoting a response but there are a number of other factors that influence whether a volcano will be triggered. Further to this, Farías *et al*. (2014) examined the response of Nevados De Chillián, Chile following two aftershocks of the 2010 earthquake. In each case, variable responses were recorded which Farías *et al*. (2014) suggested were related to the different incident angle of the aftershock events. This study also identified possible contamination due to previous triggering identifying the need for strict criteria in the methodology (i.e. spatial and temporal measures) to minimise the risk of falsely identifying triggered events.

Indeed, this factor has been recognised previously with a number of studies stating that analysis criteria are needed in order to remove bias (Walter and Amelung 2007; Eggert and Walter 2009). In some cases, it is unclear whether a period of volcanic activity is the result of an earthquake or not (Eggert and Walter 2009). Methods to establish the long term behaviour of a volcano are, therefore, required so that following an earthquake only confirmed cases of triggering are assessed (Watt *et al*. 2009). Another important factor is ensuring that earthquake-volcano interactions are not considered more than once (e.g. a response being attributed to more than one earthquake trigger) (Eggert and Walter 2009). In this regard, a triggering threshold may be the most appropriate approach to limit bias and ensure reliable results (Eggert and Walter 2009). For the basis of this research, therefore, a number of recommendations set out by Hill-Butler (2012) will be used to identify potentially triggered activity.

In order to understand the two-way coupling of earthquakes and volcanoes in Italy, assessments evaluated the role of stress (Patane *et al*. 1994; Nostro *et al*. 1998; Feuillet *et* *al*. 2006; Walter *et al*. 2009; Cannata *et al*. 2010). Most notably, it is recognised that triggered volcanic activity following an earthquake is influenced by an increase in stress (Nostro *et al*. 1998; Gresta *et al*. 2005), with a further study identifying the role of cumulative seismic energy release on triggering (Cigolini *et al*. 2007). A number of small magnitude earthquakes, for example, may be capable of initiating the same processes that lead to volcanic activity triggering following a large magnitude (M≥7.0) event (Latter 1971; Brodsky *et al*. 1998; Brodsky and Prejean 2005; Cigolini *et al*. 2007). With this in mind, it is apparent that the study of eruption triggering must first establish whether the triggered event resulted from a single large magnitude earthquake or a series of small magnitude events.

The 2011 M9.0 Japan earthquake marks the most recent (to date) instance of widespread triggering following an earthquake (Chao *et al*. 2013; Fujita *et al*. 2013; Kato *et al*. 2013; Ozawa and Fujita 2013; Takada and Fukushima 2013). Triggered seismicity at a number of volcanic sites (Figure 2-10) and the eruption of Shinmoedake, in particular, demonstrates the role of stress changes following the passage of seismic waves (Toda *et al*. 2011; Wang *et al*. 2011; Yukutake *et al*. 2011; Chao *et al*. 2013; Fujita *et al*. 2013; Kato *et al*. 2013; Ozawa and Fujita 2013; Takada and Fukushima 2013). In support of previous studies, these interactions suggest a threshold exists for a response to occur (Yamazaki *et al*. 2011; Yukutake *et al*. 2011; Fujita *et al*. 2013). In particular, it has been suggested that for an earthquake to capable of influencing volcanic activity, the stress changes resulting from an earthquake must exert significant pressures on a volcanic system. In view of this, it is possible that the stress changes resulting from an earthquake may not be large enough to trigger new activity.

FIGURE 2-10 INCREASED SEISMICITY AT HAKONE VOLCANO FOLLOWING THE 2011 JAPAN (M9.0) EARTHQUAKE (SOURCE: YUKUTAKE *ET AL*. 2011: 739).

Prior to 2011 M9.0 earthquake, Japan appeared uniquely placed due to its long history of earthquake-volcano research (Nakamura 1971; Yokoyama 1971; Kimura 1976; Rikitake and Sato 1989), yet had fewer instances of recorded responses (Harrington and Brodsky 2006). Comparisons to other earthquake-volcano interactions around the world would, therefore, allow an assessment of the parameters that trigger a response. Indeed, comparisons of triggered seismicity in Japan to case studies from the Western United States suggested that different triggering conditions may exist in different sub-regions (Harrington and Brodsky 2006). Similar findings were also noted by Alam and Kimura (2004) and Watt *et al*. (2009) who suggested enhanced relationships within volcanic arcs.

It is equally apparent that following large magnitude events, the majority of triggered responses occur aligned with the fault rupture (La Femina *et al*. 2004; Sánchez and McNutt 2004; Pollitz and Johnston 2006). Following the 1992 Landers earthquake, California, areas of triggered seismicity were located North of the main event (Hill *et al*. 1993; Anderson *et al*. 1994; Bodin and Gomberg 1994; Hill 2008), whereas following the 2002 Denali Fault earthquake, Alaska, all responses were located South-East in an area of critical stress (Husen *et al*. 2004a; Moran *et al*. 2004). While these responses indicate that the directivity of radiated energy plays an important role in the triggering mechanism (Gomberg *et al*. 2001, Sánchez and McNutt 2004), it also suggests that fault characteristics, to some extent, control the location of triggered seismicity. Sánchez and McNutt (2004), in particular, show that areas of increased seismicity are aligned with the azimuth of fault rupture, whilst areas of decreased seismicity are located perpendicular to the fault rupture. Although fewer documented periods of decreased seismicity have also been observed following an earthquake (Sánchez and McNutt 2004; Toda *et al*. 2011; Hill-Butler 2012; Lesage *et al*. 2014), it is possible that events such as those experienced at Mount Wrangell (50% decrease in activity) and Mount Veniaminof (80% decrease in activity) following the 2002 Denali Fault earthquake, Alaska (Sánchez and McNutt 2004), are just as common. In particular, constraints related to the availability of appropriate data may result in decreased volcanic activity being misidentified in observational records.

In addition to these sub-aerial responses, Oura *et al*. (1992) and Bohnenstiehl *et al*. (2014) observed instances of triggering at sub-marine volcanoes. Critically, Bohnenstiehl *et al*. (2014) noted both regional and global responses but suggest that a volcano must be in a critical state to be susceptible to triggering. Therefore while less documented these responses, like decreased activity, may be just as common.

2-3-5 KEY CHALLENGES TO EARTHQUAKE-VOLCANO RESEARCH

It is widely agreed that the relationship between earthquakes and volcanic activity results from a complex set of interactions (i.e. processes that initiate a period of unrest) that vary at a temporal and spatial scale (Hill *et al*. 2002; Manga and Brodsky 2006; Battaglia *et al*. 2012; Pritchard *et al*. 2013). However, the combination of these influencing parameters alongside varying methods of analysis has resulted in a number of challenges that threaten the overall benefits of earthquake-volcano research. Section 2-3-4 (pg. 24) showed that one of the largest pressures is the availability of appropriate data. Although there is an abundance of research using historic or observational records to investigate any relationship there are a number of limitations associated with their use (Hill *et al*. 2002). Both Eggert and Walter (2009) and Watt *et al*. (2009) state that the use of secondary data may result in difficulties interpreting the information, the use of unreliable sources or incomplete records. Figure 2-11, for example, demonstrates that since 1900 records of volcanic eruptions in South America have increased. With this in mind, the findings of Darwin (1840) may be incomplete due to the absence of volcano monitoring techniques. The availability of instrumental data, therefore, marks a significant improvement in the analysis of volcanic activity following earthquakes (Eggert and Walter 2009).

FIGURE 2-11 INCREASES IN RECORDED VOLCANIC ERUPTIONS IN SOUTH AMERICA, 1500-2000 (SOURCE: WATT *ET AL*. 2009: 401).

Emerging from the assessments detailed in Section 2-3-3 (pg. 18), Table 2-1 outlines each of the parameters identified by previous research to be capable of influencing the relationship between earthquakes and volcanic activity. Often, investigations of earthquake-volcano interactions identified a relationship that varied spatially and temporally. However, failures to consider all the parameters that may influence the relationship have meant that the reasons for these variations in response were not determined. A key challenge, therefore, is the development and implementation of an appropriate method that incorporates these parameters as criteria for analysis. Temporally, short delays could reflect the critical state of the volcanic system, whereas longer response times could occur at systems below the critical state but where stress changes are large enough to initiate processes that will culminate in an eruption (Feuillet *et al*. 2011; Lupi *et al*. 2012; Marzocchi and Bebbington 2012; Bonali 2013; Jay *et al*. 2013). In this respect, the timescale for analysis must be appropriate so that all possible interactions are analysed whilst minimising the number of false interactions. Selva *et al*. (2004), Alam *et al*. (2010) and Cannata *et al*. (2010) identify this factor as particularly challenging due to the fact that a volcano's response may first result in seismicity and deformation that then culminates in an eruption. Based on this, there is a risk that the triggering earthquake is incorrectly identified. Similarly, examples of the spatial relationship between earthquakes and volcanoes identify both proximal, within a few hundred kilometres, and global responses. To reliably analyse any relationship, therefore, investigations need to be conducted at a global and regional scale to obtain a clear understanding of sub-regional influences (Watt *et al*. 2009).

Although the majority of responses result in an increase in volcanic activity it is often difficult to identify whether new activity has been triggered by an earthquake or initiated due to another external factor (Eggert and Walter 2009). While it is possible that the clustering of earthquakes and volcanic activity is the result of coincidence, there is a need to know whether the events under study are triggered (Freed 2005; Yamazaki *et al*. 2011). As a result, an important challenge to earthquake-volcano investigations is the ability to employ appropriate analysis criteria as well as establish long-term volcanic activity so that all triggered responses can be recognised (Linde and Sacks 1998; Hill *et al*. 2002; Manga and Brodsky 2006; Watt *et al*. 2009; Dzierma and Wehrmann 2010; Battaglia *et al*. 2012).

TABLE 2-1 PARAMETERS IDENTIFIED BY PREVIOUS RESEARCH TO INFLUENCE THE RELATIONSHIP BETWEEN EARTHQUAKES AND VOLCANIC ACTIVITY.

Variable Feature	Parameter For Analysis	Proposed Influence	Documented By
Earthquake Characteristics	Earthquake Magnitude	The magnitude of the earthquake has been suggested to influence the response of volcanoes with an inverse relationship suggested between earthquake magnitude and time for response.	Carr (1977) Hill *et al*. (1993) Bodin and Gomberg (1994) Gomberg *et al*. (2001) Sánchez and McNutt (2004) Carniel and Tárraga (2006) Manga and Brodsky (2006) Walter and Amelung (2007) Delle Donne *et al*. (2010) Battaglia *et al*. (2012)
	Earthquake Rupture Length	A volcano's location to an earthquake's rupture zone is suggested to have a large influence on triggering due to the resulting stress changes.	
	Earthquake Depth	The depth of an earthquake may influence the amount of stress change acting on a magma chamber.	
	Earthquake Azimuth to Volcano	An earthquake's azimuth to a volcano may identify an optimum angle between the triggering earthquake and responding volcano in which a response is most likely. This is related to the alignment with the earthquake fault rupture.	
	Earthquake Strike	The angle of an earthquake may determine the direction of greatest stress energy and therefore which volcanoes may be more likely to respond.	
	Earthquake Dip	The angle of an earthquake may determine the direction of greatest stress energy and therefore which volcanoes may be more likely to respond.	
	Type of Earthquake	A certain type of earthquake (strike-slip, oblique reverse, reverse (thrust) or normal)) may be more likely to influence a response.	
	Incoming Earthquake Wave Direction	Volcanoes located in the zone of greatest wave energy may be more likely to respond following the passage of seismic waves.	
	Region of Earthquake	Earthquake-volcano interactions have been identified to vary between different sub-regions.	
	Tectonic Setting of Earthquake's Location	Earthquake-volcano interactions have been identified to vary between different sub-regions.	
	Tectonic Plate of Earthquake's Location	Earthquake-volcano interactions have been identified to vary between different sub-regions.	

Volcano Characteristics	Type of Response	A volcano's response can be new activity or an increase in on-going activity, when assessed alongside the time since last period of activity, it may indicate if a volcano is in a critical state.	Hill *et al*. (1993) Linde and Sacks (1998) Hill *et al*. (2002) La Femina *et al*. (2004) Lara *et al*. (2004) Moran *et al*. (2004) Sánchez and McNutt (2004) Manga and Brodsky (2006) Walter and Amelung (2007) Watt *et al*. (2009) Cannata *et al*. (2010) Delle Donne *et al*. (2010) Bebbington and Marzocchi (2011) Yamazaki *et al*. (2011) Battaglia *et al*. (2012)
	VEI of Volcanic Activity	The eruption intensity may indicate the degree of triggering and variations from normal eruptive activity.	
	Length of Volcanic Response	The length of response reflects a volcano's susceptibility to triggering.	
	Time Since Last Period of Volcanic Activity	By identifying the behaviour of the volcano, the time since last period of volcanic activity may indicate if a volcano is in a critical state.	
	Status of Volcano at Time of the Earthquake	The status of a volcano may indicate volcanoes that are more likely to respond.	
	Volcano Type	Responses may be more likely at volcanoes of a certain type.	
	Magma Composition	The chemical composition of a volcano may control the level and type of response. Volcanoes with differing chemical composition may also be influenced by different triggering mechanisms.	
	Surrounding Volcanic Geology	The geology surrounding a volcano may influence the degree of stress change following an earthquake.	
	Region of Volcano	Earthquake-volcano interactions have been identified to vary between different sub-regions.	
	Tectonic Setting of Volcano's Location	The tectonic stress change may influence the level of stress change following an earthquake and, therefore, a volcano's susceptibility to triggering.	
	Tectonic Plate of Volcano's Location	Earthquake-volcano interactions have been identified to vary between different sub-regions.	
	Type of Crust of Volcano's Location	The tectonic stress change may influence the level of stress change following an earthquake and, therefore, a volcano's susceptibility to triggering.	
Temporal Characteristics	Temporal Delay Between Triggering Earthquake and Responding Volcano	The delay between triggering earthquake and responding volcano is thought to indicate the susceptibility and degree of triggering based on other parameters e.g. distance or earthquake magnitude.	Hill *et al*. (2002) Marzocchi (2002) Manga and Brodsky (2006) Eggert and Walter (2009)

Spatial Characteristics	Distance	Volcanoes at an optimum distance from the earthquake epicentre may be more likely to respond. In addition, if a number of parameters influence a response, it may be that a number of criteria need to be met for a response to occur.	Hill *et al*. (1993) Marzocchi *et al*. (2004) West *et al*. (2005) Manga and Brodsky (2006) Harrington and Brodsky (2006) Eggert and Walter (2009) Watt *et al*. (2009)
	Location of Volcano in Relation to Earthquake	A volcano's location in relation to the earthquake fault rupture is thought to influence whether an increase or decrease in activity would be experienced.	
Stresses	Volcanic Compression or Dilatation	Following an earthquake, volcanoes located in an area of critical stress change may be more susceptible to triggering following the passage of seismic waves. The change in stress may also indicate the triggering mechanism initiating a response.	Marzocchi *et al*. (2002) Cigolini *et al*. (2007) Walter and Amelung (2007) Wang *et al*. (2011) Chesley *et al*. (2012)

Finally, while the methods used to identify instances of potentially triggered earthquake-volcano interactions (i.e. comparisons of volcanic activity before and after an earthquake) are comparable, there is no defined threshold to identify a responding volcano. With the exception of Harris and Ripepe (2007) and Delle Donne *et al*. (2010), who identified a change in activity of at least 100% as a threshold for response, the majority of investigations did not employ a threshold to identify triggered activity. The assessment of observational records (e.g. Linde and Sacks 1998; Magna and Brodsky 2006; Eggert and Walter 2009), for example, were based on temporal changes in eruption rates while more recent examinations of triggered activity using ground-based measurements (e.g. Richter *et al*. 2004; Cigolini *et al*. 2007) were based on retrospective analyses at selected volcanoes with a confirmed concurrence of seismic and volcanic activity. This research will, therefore, use a number of recommendations (including a threshold for triggering based on analyses by Harris and Ripepe (2007) and Delle Donne *et al*. (2010)) by Hill-Butler (2012) to aid the identification of potentially triggered earthquake-volcano interactions.

2-3-6 APPLICATION OF REMOTE SENSING FOR EARTHQUAKE-VOLCANO INTERACTIONS RESEARCH

In recent years, studies have also began to focus on the use of remotely sensed data (further discussed in Section 2-4, pg. 43) to monitor changes in a volcano's character. The availability of volcanic radiant flux data highlights the potential of these methods to investigate the response of volcanoes to earthquakes (e.g. Harris and Ripepe 2007; Delle Donne *et al*. 2010; Jay *et al*. 2013). In addition, the development of hotspot detection algorithms (Section 2-5-2, pg. 51) and methods to assess earthquake-volcano interactions (Section 2-3-2, pg. 16) tackled some of the limitations identified in previous literature.

Initial research by Moran *et al*. (2002) detailed the use of satellite imagery to investigate the eruption of Shishaldin, Alaska one month after a M5.2 earthquake. Calculating subsequent coulomb stress changes, they suggested a two-way coupling in which magma movement caused instability triggering the earthquake and subsequent eruption. Indeed, this complimentary nature of earthquakes and volcanoes has been suggested previously, however, less attention has been given to the effect of volcanic activity on earthquakes in recent years.

Research by Harris and Ripepe (2007) and Delle Donne *et al*. (2010) pioneered the use of MODVOLC detected thermal anomalies (detailed in Section 2-5-3, pg. 53) to investigate the relationship between earthquakes and volcanic activity. Although based on different spatial scales, each of these studies showed that there were significant increases in volcanic radiant flux following an earthquake. In order to fully understand the proposed response of Semeru and Merapi, Indonesia to a M6.4 earthquake, Harris and Ripepe (2007) examined the response over a 35-day window. Recognising similar patterns of triggering at both volcanoes, changes in stress were attributed as the cause of this relationship with delayed responses being due to the time it takes for changes in the magma chamber to be reflected at the earth's surface.

Delle Donne *et al*. (2010) also observed regional and global responses with similar characteristics demonstrating that earthquakes can initiate new activity if a volcano is in a critical state as well as modify on-going eruptions. Comparing cumulative radiative power (as calculated by Kaufman *et al*. 1998, Eq. 2-5 pg. 56) to the cumulative seismic energy of all earthquakes 2000-2006, they showed that at a global scale 4 out of 7 M≥7.8 earthquakes had a subsequent increase in volcanic radiant flux, Figure 2-12 (Delle Donne *et al*. 2010). Crucially, Delle Donne *et al*. (2010) showed that the biggest increase in volcanic radiant flux was following the 2004 Boxing Day earthquake (Figure 2-12), supporting previous research which identified triggering following this event (West *et al*. 2005; Harrington and Brodsky 2006; Walter and Amelung 2007; Okubo and Wolfe 2008).

FIGURE 2-12 CUMULATIVE SEISMIC ENERGY (GREY LINE) COMPARED TO CUMULATIVE VOLCANIC RADIANT FLUX (BLACK LINE), 2000-2006. RED CIRCLE INDICATES INCREASE IN RADIANT FLUX FOLLOWING THE 2004 SUMATRA EARTHQUAKE (SOURCE: DELLE DONNE *ET AL*. 2010: 773).

Despite this work being initially compelling, Hill-Butler (2012) demonstrated that the methodology and results of the regional assessment have a number of inconsistencies. In particular, re-inspection of the data and methods found discrepancies with the results presented, this resulted in all regional responses producing weaker correlations limiting the overall significance reported by Delle Donne *et al*. (2010), Table 2-2 (Hill-Butler 2012). In addition, it was noted that the regional results presented by Delle Donne *et al*. (2010) were based on data at a regional and global scale (Hill-Butler 2012). Further shortcomings include volcanoes claimed as responding not meeting the response criteria, the use of qualitative earthquake-volcano interactions (negating the use of satellite-derived radiant flux) and the use of the correlation co-efficient (R) and not the R^2 value (overestimating the strength of the relationship) (Hill-Butler 2012). As such, Hill-Butler (2012) made a set of recommendations that could be incorporated into future investigations using satellite-derived radiant flux data:

- The use of a longer response window to allow for the normal activity of a volcano to be reflected.
- The calculation of radiative power based on percentages, as set out by Harris and Ripepe (2007), to enable changes in activity to be identified.
- A minimum number of data points in order to positively identify an eruption and limit the misuse of wild fire detections.
- Investigations of volcanoes that show multiple responses to allow case-specific earthquake-volcano interactions to be examined.

TABLE 2-2 CORRELATIONS PRESENTED BY DELLE DONNE *ET AL*. (2010) COMPARED TO CORRELATIONS REPORTED BY HILL-BUTLER (2012) FOLLOWING THE METHOD DETAILED BY DELLE DONNE *ET AL*. (2010).

As detailed in Section 2-3-3 (pg. 18), deformation changes have also been noted following seismic events. The use of InSAR (outlined in Section 2-4-3, pg. 46) has particular utility to measure deformation changes at volcanic centres following an earthquake. Within this context, Feigl *et al*. (2000) used InSAR data to show that a two-way coupling exists between volcanic unrest and local seismicity at Hengill volcano, Iceland. Most recently, assessments following the 2010 M8.8 Chile and 2011 M9.0 Japan earthquakes have detailed subsidence of up to 15 cm at volcanic centres following these events (Ozawa and Fujita 2013; Pritchard 2013; Pritchard *et al*. 2013; Takada and Fukushima 2013). Importantly, while Pritchard *et al*. (2013) and Takada and Fukushima (2013) detected similar cases of volcanic deformation following the 2010 M8.8 Chile earthquake and the 2011 M9.0 Japan earthquake (respectively), each study suggests differing causal mechanisms for this type of response. Despite this, these occurrences of volcanic subsidence may indicate that this form of response may be more common but the availability of data to examine such changes has hindered previous investigations of this type. Another important observation was that while both these events were followed by changes in deformation, no eruptive responses were observed. The reasons for this, however, are unclear. By comparing this event to previous cases of triggering as well as volcanoes with no triggered activity it may, therefore, be possible to identify the parameters that influence whether a response occurs.

2-3-7 PROPOSED MECHANISMS OF RESPONSE

As discussed in Section 2-3-3 (pg. 18), a reoccurring theme within the analysis of earthquake-volcano interactions is the role that changes in stress have on the relationship (Brodsky *et al*. 1998; Gomberg and Davis 1996; Walter and Amelung 2006; Walter *et al*. 2007; Prejean and Haney 2014). Despite this, there is no clear evidence that supports a mechanism for response. Focusing on the passage of seismic waves, many studies have suggested that an earthquake may trigger volcanic activity by static or dynamic stress change (Walter and Amelung 2007). Static stresses act, predominately, in regions close to an earthquake's rupture zone (Hill *et al*. 2002). These stresses result in a permanent stress change and are caused by displacement during an earthquake (Walter and Amelung 2007; Eggert and Walter 2009). In contrast, dynamic stresses are induced during the passage of seismic waves, decaying more slowly ($1/r^{1.66}$ as compared to $1/r^3$ where r is the distance) away from an earthquake source (Hill *et al*. 2002; Manga and Brodsky 2006; Bebbington and Marzocchi 2011). These stresses, however, are short-lived and require a mechanism to transfer them to permanent stress following the passage of seismic waves (Manga and Brodsky 2006).

The link between rupture propagation and zone of triggered responses supports a mechanism related to rupture directivity (Hill *et al*. 1995; Manga and Brodsky 2006; Bonali *et al*. 2015). Delle Donne *et al*. (2010), for example, propose that the selectivity of responses detailed in previous literature results from the concentration of wave energy along a certain path (Gomberg *et al*. 2001; USGS 2012). Therefore volcanoes which are likely to experience an increase in activity may be located on the azimuth of fault rupture and volcanoes which experience a decrease in activity may be located perpendicular to the fault rupture as suggested by Sánchez and McNutt (2004), Figure 2-13.

FIGURE 2-13 CHANGE IN COULOMB STRESS FIELD FOLLOWING THE 2002 DENALI FAULT EARTHQUAKE, ALASKA. RED INDICATES POSITIVE CHANGES IN COULOMB STRESS (ENCOURAGING FAILURE) AND BLUE REPRESENTS NEGATIVE CHANGES IN COULOMB STRESS (INHIBITING FAILURE) (ADAPTED FROM: SÁNCHEZ AND MCNUTT 2004: 380).

The role of bubbles within the magmatic system has also been identified as an important factor in earthquake-volcano interactions (Cannata *et al*. 2010). Rectified diffusion results when the passage of seismic waves excites bubbles within the magma chamber, causing overpressure and culminating in an eruption, Figure 2-14 (Sturtevant *et al*. 1996; Brodsky *et al*. 1998; Lara *et al*. 2004). It is suggested that this mechanism results in a transfer of stress from dynamic to static stress and that fluid dynamics play an important role in triggering (Hill *et al*. 1995; Brodsky *et al*. 1998; Brodsky 2001). Further research by Ichihara and Brodsky (2006), however, showed that rectified diffusion only increased the pressure within the magma chamber rather than causing an excitation of bubbles. Therefore, based on these findings, rectified diffusion may only contribute to the triggering of volcanic activity, with a number of other factors also controlling a volcano's response (Ichihara and Brodsky 2006).

FIGURE 2-14 MECHANISM OF RECTIFIED DIFFUSION WHEREBY SEISMIC WAVES PUMP VOLATILES INTO A BUBBLE INCREASING ITS VOLUME AND PRESSURE WHICH IS THEN SUBSEQUENTLY COMPRESSED (SOURCE: STURTEVANT *ET AL*. 1996: 25,271).

Advective overpressure has also been shown to be capable of triggering activity following the excitation of bubbles (Linde *et al*. 1994; Hill *et al*. 2002). In contrast to rectified diffusion, advective overpressure results when bubbles within the magma chamber are shaken loose following the passage of seismic waves (Linde *et al*. 1994; Brodsky and Prejean 2005). As the bubbles rise, instability within the magma chamber creates an increase in pressure (Sahaglan and Proussevitch 1992; Pyle and Pyle 1995; Brodsky and Prejean 2005; Manga and Brodsky 2006). This mechanism, in particular, supports the triggered seismicity and deformation reported at Long Valley Caldera following the 1992 Landers earthquake, California (Hill *et al*. 2002). What is more, it is possible that this mechanism accounts for the delayed responses that have been observed following triggering (Hill *et al*. 2002).

In the near field (<750 km), earthquake-induced decompression is suggested to cause triggering due to static stress (Eggert and Walter 2009). The build-up of stress induced by an earthquake results in volumetric expansion beneath a volcano, Figure 2-15, causing bubble excitation or overpressure and encouraging an eruption, Figure 2-16 (Walter and Amelung 2006; Walter and Amelung 2007; Lupi *et al*. 2012). Further support for this mechanism was reported following the 2011 M9.0 Japan earthquake. In particular, Wang *et al*. (2011) calculated changes in the regional stress field identifying volumetric expansion beneath 3 volcanic centres including Shinmoedake that erupted 2 days after the earthquake.

Figure 2-15 Areas of volumetric expansion (red) and contraction (blue) following an earthquake (Source: Walter and Amelung 2007: 541).

Figure 2-16 Proposed triggering mechanisms due to earthquake deformation (Source: Walter and Amelung 2007: 541).

Similarly, quasi-stress triggering has been suggested to influence the crust within a volcanic system. Most often acting in the near field, viscoelastic relaxation (demonstrated in Figure 2-17) occurs when the stress released by an earthquake is transferred to a volcano's elastic crust (Hill *et al*. 2002; Marzocchi 2002; Marzocchi *et al*. 2002; McNutt and Marzocchi 2004; Cigolini *et al*. 2007; De la Cruz-Reyna *et al*. 2010; Bebbington and Marzocchi 2011). This stress change then causes seismicity and crustal deformation until the system reaches a new equilibrium whether it is a new eruption or a decrease in unrest (Marzocchi *et al*. 2002; De la Cruz-Reyna *et al*. 2010; Delescluse *et al*. 2012).

Figure 2-17 Schematic diagram of the different regions beneath a volcanic system. 1) solid, rigid crust; 2) viscoelastic region; 3) magma reservoir; 4) marred region occluding magma (Source: De la Cruz-Reyna *et al*. 2010:46).

In relation to the 2011 Japan earthquake, an important observation made following the event resulted from comparisons to the 2010 Chile earthquake. In both scenarios, responses of increased deformation were recorded. The suggested causal mechanisms, however, were notably different. While Pritchard *et al*. (2013) suggested that co-seismic extension caused the release of hydrothermal fluids; Takada and Fukushima (2013) surmised that changes in deformation resulted from the sinking of the magma reservoir and surrounding rock. As such, understanding the parameters that influence a volcano's response is critical to understand and infer mechanisms of triggering.

Further mechanisms that have been suggested to affect the response of volcanoes to earthquakes are detailed in Table 2-3. Alongside these mechanisms, it has been suggested that each volcano has a number of factors that have a role in triggering (Woods and Pyle 1997; Hill *et al*. 2002; Manga and Brodsky 2006). One idea identified to be gaining emphasis is the existence of triggering thresholds (Johnston *et al*. 1995; Sturtevant *et al*. 1996; Brodsky 2001; Husen *et al*. 2004a; Brodsky and Prejean 2005; Watt *et al*. 2009). Moran *et al*. (2004), in particular, outlined a triggering threshold for earthquakes located within 10,000 km of Katmai volcano, Alaska, Figure 2-18. In the same way that local conditions may control the dominant process of response (Hill *et al*. 1993), it is suggested that a volcano's triggering threshold depends on the volcanic system (Moran *et al*. 2004). In this respect, the existence of a triggering threshold may explain why a volcano does or does not respond (Anderson *et al*. 1994). As such, a review of case-specific earthquake-volcano interactions is required to identify favourable conditions for eruptions.

FIGURE 2-18 PROPOSED TRIGGERING THRESHOLD AT KATMAI VOLCANO, ALASKA FOLLOWING CASES OF TRIGGERED SEISMICITY (SQUARES) AND CASES WHEN TRIGGERING DID NOT OCCUR (CIRCLE) (SOURCE: MORAN *ET AL*. 2004: 307).

TABLE 2-3 ALTERNATIVE MECHANISMS OF RESPONSE

Mechanism of Response	Description	Previous Research
Relaxing Magma Body	Seismic waves following an earthquake can disrupt a partially crystallised magma chamber, releasing stress and deforming the surrounding crust triggering local seismicity.	Johnston *et al*. (1995) Hill *et al*. (2002) Lupi and Miller (2014)
Sinking Crystal Plume (Falling Roofs or Magmatic Overturn)	Passing seismic waves can dislodge crystals located on the walls and ceiling of the magma chamber. This causes convection in the magma chamber causing bubble formation and nucleation leading to an increase in overall pressure.	Hill *et al*. (2002) Manga and Brodsky (2006)
Hydraulic Surge	Dynamic stress associated with the passage of seismic waves disrupts the impermeable seal between the plastic crust and the magma body, releasing fluid into the hydrothermal system which can increase pressure within the magma chamber.	Hill *et al*. (2002)
Magmatic Overpressure	Volcanoes below their critical state but where the stress changes are large enough to initiate a process of response resulting in delayed triggered.	Eggert and Walter (2009)
Creating New Bubbles (Bubble Nucleation)	This mechanism most often affects volcanoes that are close to volatile saturation. Following the passage of seismic waves, the pressure change associated with dynamic stresses can cause rapid bubble nucleation leading to an eruption.	Manga and Brodsky (2006)
Crustal Dilatation (Unclamping)	Following an earthquake a volcano is affected by a reduction in static stress. This process of dilatation or unclamping allows magma to move along unclamped pathways promoting dyke intrusion.	Hill *et al*. (2002) Walter (2007) Bonali (2013) Bonali *et al*. (2013) Bonali *et al*. (2015)

2-3-8 SUMMARY

Overall, it is clear that a combination of factors control the response of volcanoes to earthquakes. While the mechanisms suggested all require a change in stress to trigger unrest, regional characteristics and the state of the volcanic system may control whether a response occurs. As such, it is possible that more than one mechanism may be involved in triggering (Husen *et al*. 2004a; Prejean *et al*. 2004; Harrington and Brodsky 2006; Shuler 2012). West *et al*. (2005), for example, suggest that if the conditions leading to triggering vary globally then the mechanism controlling a response will also be different. Conversely, Watt *et al*. (2005) suggested that each mechanism acts on different timescales. Therefore, to gauge the effect of the relationship at different scales, investigations at sub-regional and global scales need to be conducted to attribute mechanisms of response.

2-4 VOLCANIC REMOTE SENSING

In the last few decades, satellite remote sensing of volcanoes and their products has become increasingly important. There are now a suite of complimentary datasets ranging from ultraviolet wavelengths (300 nm) to microwaves (30 cm) that can be applied to detect subsurface changes in a volcano's profile, identify precursory changes in activity and provide key observations on the progression of volcanic hazards, Figure 2-19 (Oppenheimer 1998; Mouginis-Mark and Domergue-Schmidt 2000; Dean *et al*. 2002; Pieri and Abrams 2004; Pritchard and Simons 2004; Stevens *et al*. 2004; Hooper *et al*. 2012; Webley *et al*. 2012; Pritchard *et al*. 2013; Pyle *et al*. 2013). The ability to now monitor and observe the full eruption cycle from pre-eruptive processes to post-eruption volcanic hazards has exploited the varying spatial, spectral and temporal capabilities of sensors to provide information that would not otherwise be available (Dean *et al*. 2002; Pritchard and Simons 2004; Hooper *et al*. 2012; Webley *et al*. 2012; Pyle *et al*. 2013). As a result, satellite observations now represent a vital tool providing timely and synoptic information about volcanic hazards and their products.

FIGURE 2-19 APPLICATION OF REMOTE SENSING TECHNIQUES TO MONITOR VOLCANIC ACTIVITY DURING A PERIOD OF UNREST. BASED ON THE TYPE OF UNREST EXPERIENCED, DIFFERENT SYSTEMS ARE UTILISED TO MONITOR THE PROGRESSION OF ACTIVITY (SOURCE: PYLE *ET AL*. 2013: 2).

The launch of sensors capable of monitoring volcanic activity (e.g. ALOS (Advanced Land Observing Satellite), ASTER (Advanced Spaceborne Thermal Emission and

Reflection Radiometer), ENVISAT (Environmental Satellite), ERS (European Remote Sensing Satellite), MODIS (Moderate Resolution Imaging Spectroradiometer), Landsat and Sentinel) has seen a variety of techniques being developed to monitor and track volcanic hazards at a global scale (Oppenheimer 1998; Di Bello *et al*. 2004; Wright *et al*. 2002; Gillespie *et al*. 2007; Wooster 2007; Torres *et al*. 2012; Murphy *et al*. 2013; Roy *et al*. 2014). For example, the rapid dispersal of volcanic emissions from ash clouds pose a significant threat for the aviation industry. Therefore, the provision of dispersal information from sensors such as AVHRR (Advanced Very High Resolution Radiometer) enables volcanic ash clouds to be tracked thousands of kilometres from their source as well as providing information on their 3D profile (i.e. plume height) (Pergola not published; Pyle *et al*. 2013). Digital Elevation Models (DEMs) generated by information from ASTER and STRM (Shuttle Radar Topography Mission) are also enabling hazard maps to be developed (Stevens *et al*. 2004; Pyle *et al*. 2013). This application is critical to model volcanic flow processes as well as inform hazard assessments (Stevens *et al*. 2004; Pyle *et al*. 2013). Finally, geostationary platforms offer greatly improved monitoring capabilities providing timely and continuous data for certain regions (Pergola not published). Dean *et al*. (2002), in particular, demonstrated the advantages of geostationary sensors such as GOES (Geostationary Operational Environmental Satellite) and GMS (Geostationary Meteorological Satellite) for routine monitoring and real-time detection of volcanic thermal features and ash clouds in the North Pacific. Overall, the availability of sensors equipped to monitor volcanic features marks a critical application providing timely information on the progression of volcanic hazards as well as improving our understanding of volcanic processes. The following sections will now provide a brief outline of the main applications of volcanic remote sensing and, finally, provide an overview of the use of satellite information for volcanology.

2-4-1 VOLCANIC THERMAL HOTSPOTS

The identification of thermally anomalous volcanic features (e.g. lava lakes, lava flows, lava domes, fumaroles, pyroclastic flows, steam venting and degassing) is, perhaps, the most widely documented use of satellite remote sensing for volcanic detection (Oppenheimer *et al*. 1993; Harris and Stevenson 1997; Harris *et al*. 2000; Wright *et al*. 2002; Rothery *et al*. 2005). Since its initial use as a qualitative tool by Gawarecki *et al*. (1965) to discriminate lava flows at Kilauea and Mauna Loa, Hawai'i; the number of sensors (including ASTER, ATSR (Along Track Scanning Radiometer), AVHRR, GOES, Landsat and MODIS) equipped with thermal capabilities to monitor thermal hotspots has grown dramatically (Harris *et al*. 2000; Flynn *et al*. 2002; Blackett 2014). As a result, many of the current methods use an automated approach in which the calculated difference between the Middle Infrared (MIR) and Thermal Infrared (TIR) wavebands can identify hotspots in near real-time, Figure 2-20 (Kaufman *et al*. 1998; Harris *et al*. 2000; Pieri and Abrams 2005; Wright and Pilger 2008; Koeppen *et al*. 2011). In particular, in showing the use of ASTER data to monitor thermal activity at Mount St. Helens, Vaughan and Hook (2006) were able to correlate changes in thermal behaviour with periods of increased volcanic activity. In doing so, Vaughan and Hook (2006) suggested that there is potential to use these precursory changes to forecast impending activity, a factor which has been studied extensively using data from ASTER and other high-temporal resolution sensors (Carn and Oppenheimer 2000; Dehn *et al*. 2000; Dean *et al*. 2002; Pieri and Abrams 2004; Pieri and Abrams 2005; Webley *et al*. 2008; Hooper *et al*. 2012; van Manen *et al*. 2013).

FIGURE 2-20 DETECTIONS OF ASTER THERMAL HOTSPOTS DETECTIONS AT NEVADOS DE CHILLIÁN, CHILE. A) NORMAL BACKGROUND RADIANCE, B) THERMAL HOTSPOT RELATED TO A PERIOD OF UNREST IN JUNE 2008 AND C) RETURN TO BACKGROUND THERMAL ACTIVITY (SOURCE: JAY *ET AL*. 2013: 178).

2-4-2 VOLCANIC ASH CLOUDS

In terms of volcanic ash cloud monitoring, the significance of TIR wavebands has been noted since the 1980s (Rothery *et al*. 1988). In the same way that thermal anomaly detections use TIR channels to discriminate volcanic hotspots, TIR is used operationally to identify volcanic ash clouds based on their radiative differences from meteorological clouds (Ellrod *et al*. 2003; Watson *et al*. 2004; Marchese *et al*. 2010; Webley *et al*. 2012). In providing synoptic information about volcanic ash clouds in the North Pacific, the Alaska Volcano Observatory showed the potential to forecast and model their movement using Volcanic Ash Transport and Dispersion (VATD) models, Figure 2-21 (Francis and Rothery 2000; Dean *et al*. 2002; Webley *et al*. 2009). In recent years, airspace closures following eruptions in Iceland, Indonesia and South America have demonstrated the advantages of satellite remote sensing to provide forecasts on the future movement of volcanic ash clouds (Webley *et al*. 2012; Pyle *et al*. 2013). Without such forecasts the economic losses following the 2010 eruption of Eyjafjallajökull, for example, would have been much more significant (Christopher *et al*. 2012; Webley *et al*. 2012).

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FIGURE 2-21 MODEL SIMULATION OF VOLCANIC ASH MOVEMENT FOLLOWING THE ERUPTION OF EYJAFJALLAJÖKULL APRIL 14TH 2010 (A) TO APRIL 19TH 2010 (F). RED TONES INDICATE HIGH CONCENTRATIONS OF ASH (SOURCE: WEBLEY *ET AL*. 2012: 6).

2-4-3 DEFORMATION

In addition to IR monitoring of volcanoes, the application of radar interferometry to monitor changes in surface deformation has been widely documented (Francis and Rothery 2000; Harris *et al*. 2000; Dean *et al*. 2002; Pritchard and Simons 2004; Kervyn *et al*. 2008; Joyce *et al*. 2009; Aschbacher *et al*. 2014). Based on the comparison of two radar images, subtle changes in a volcano’s topography can be assessed to identify magma movement or an impending eruption, Figure 2-22 (Francis and Rothery 2000; Mouginis-Mark and Domergue-Schmidt 2000; Zebker *et al*. 2000; Pritchard and Simons 2004; Kervyn *et al*. 2008; Hooper *et al*. 2012). Although the principles of Interferometric Synthetic Aperture Radar (InSAR) date back to the early 1970s, it was not until the launch of the ERS-1 satellite in 1991 that large SAR datasets were available (Bamler and Hartl 1998;

Burgmann *et al*. 2000; Francis and Rothery 2000). Since then, the utility of InSAR has evolved rapidly and, following its application to measure deformation changes at Mount Etna by Massonet *et al*. (1995), has been recognised as a potential method for routine volcano monitoring (Francis and Rothery 2000; Ramsey and Flynn 2004; Hooper *et al*. 2012). Until the recent launch of the Sentinel-1 satellite in April 2014, however, routine monitoring of volcanic deformation using InSAR has not been possible (Torres *et al*. 2012; Aschbacher *et al*. 2014).

FIGURE 2-22 INTERFEROGRAMS FOR FOUR VOLCANIC AREAS IN SOUTH AMERICA, EACH CONTOUR REPRESENTS 5 CM OF DEFORMATION (SOURCE: PRITCHARD AND SIMONS 2004: 6).

2-4-4 APPLICATIONS OF VOLCANIC REMOTE SENSING

Overall, volcanic remote sensing offers a number of specific advantages providing information on volcanoes that are often inaccessible or too remote to warrant routine ground observations as well as reducing the need for direct measurements (see Section 1-2, pg. 4). There are, therefore, a number of applications of remotely sensed data that will enable us to improve our understanding of volcanoes as well as monitor volcanic hazards. At the forefront of these, is the ability to integrate observations to model volcanic processes. Perhaps the most wide-ranging hazard is the dispersal of volcanic ash clouds. By collecting information on gas emissions and tracking the dispersal of ash, operational forecast models have been developed that predict the extent of dispersal and plume evolution, Figure 2-21 (e.g. Ellrod *et al*. 2003; Webley *et al*. 2012). In recent years, this information has been critical in providing warnings to the aviation industry (Webley *et al*. 2012). Another important application of remotely sensed data has been for operational modelling. These models, in particular, have provided the opportunity to conduct scenario-based hazard assessments as well as develop hazard maps (Stevens *et al*. 2004; Mouginis-Marks and Garbeil 2005; Kervyn *et al*. 2008). This application of volcano monitoring has greatly enhanced hazard management as well as enabling the real-time progression of hazards to be monitored and mitigated (Pyle *et al*. 2013). Finally, in addition to operational forecasting and modelling, the integration of remotely sensed data with ground-based observations is enabling the processes that underlie volcanic activity to be modelled improving our understanding of how and why a volcano erupts.

2-5 THE BASICS OF THERMAL REMOTE SENSING

As discussed in Section 2-4-1 (pg. 44), one method to identify volcanic thermal anomalies is based on the calculated difference between radiances in the MIR and TIR wavebands (Harris *et al*. 1995; Kaufman *et al*. 1998; Harris *et al*. 2000; Wright *et al*. 2004; Kervyn *et al*. 2006; Koeppen *et al*. 2011). Also termed 'active' fire detection (Hawbaker *et al*. 2008), the theoretical basis for the identification of thermal anomalies relies on Planck's Law:

Eq. 2-2

Where $L_\lambda(T)$ is Planck's Function (W m^{-2} sr^{-1} m^{-1}), (T) is the temperature of the blackbody, λ is the wavelength and C_1 and C_2 are constants 1.19 x 10^{-16} W m $^{-2}$ sr^{-1} and 1.44 x 10^{-2} m K, respectively (Planck 1901). Which dictates that as the temperature of a thermally anomalous pixel increases, the peak wavelength of emitted radiances decreases, Figure 2-23, and the Stefan-Boltzmann Law which governs that as the temperature of a surface increases, so too does the radiance emitted (Kaufman *et al*. 1998; Wooster and Rothery 2000; Flynn *et al*. 2002; Wright and Pilger 2008; Hooper *et al*. 2012):

Eq. 2-3

Where E = emitted radiance (W m^{-2}), σ = Stefan-Boltzmann Constant (5.6697 x 10^{-8} W m^{-2} K^{-4}) and T = temperature of blackbody (K) (Stefan 1879; Boltzmann 1884). As a result, within an otherwise thermally homogeneous environment, the amount of radiance detected in the MIR waveband (i.e. a thermal hotspot) will be significantly higher than the radiance detected in the TIR waveband (i.e. the cooler surface), demonstrated in Figure 2-24 (Wright *et al*. 2002; Wright *et al*. 2004; Wright and Pilger 2008; Giglio 2010).

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FIGURE 2-23 CALCULATED DIFFERENCE BETWEEN DETECTED RADIANCES IN THE MIR (3.959μM) AND TIR (12.02 μM) WAVEBANDS AS DEFINED BY PLANCK'S LAW (SOURCE: WRIGHT *ET AL*. 2002: 5).

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FIGURE 2-24 DIFFERENCE IN DETECTED RADIANCES FOR MIR (3.959 μM) AND TIR (12.02 μM) WAVELENGTHS FOR A THERMALLY ANOMALOUS FEATURE. EXAMPLE BASED ON ATSR DATA FROM MOUNT ETNA, ITALY 17TH MARCH 1998 (SOURCE: WRIGHT *ET AL*. 2004: 31).

2-5-1 THE MODIS SENSOR

A number of sensors (ASTER, ATSR, AVHRR, GOES, Landsat and MODIS) exist which have been shown to be capable of monitoring the thermal behaviour of volcanoes. Of these, the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on-board

NASA's Terra and Aqua platforms has been recognised as a reliable tool for volcanic hotspot monitoring due to its high temporal frequency providing near daily global coverage (Mouginis-Mark *et al*. 1991; Kaufman *et al*. 1998; Flynn *et al*. 2002; Justice *et al*. 2002; Wright *et al*. 2002; Wright *et al*. 2004). The MODIS sensor has a total of 36 spectral bands, 10 of which have specific utility for the detection of volcanic features (Kaufman *et al*. 1998; Flynn *et al*. 2002; Wright *et al*. 2002). In particular, detected radiances at 3.959µm (MIR) and 12.02 µm (TIR) coincide with peak emissions for volcanic thermal anomalies and ambient surface temperatures, respectively (Kaufman *et al*. 1998; Wright *et al*. 2002). In terms of hotspot detection, both MODIS Bands 21 and 22 have been shown to accurately identify volcanic thermal features (Wright *et al*. 2002; Wright *et al*. 2004). Both Bands 21 and 22 account for quantization error and noise, however despite its lower saturation temperature (340 K compared to 500 K), radiances as detected by Band 22 are preferable due to its higher radiometric accuracy 0.07 K (Band 21 – 2.00 K) (Kaufman *et al*. 1998; Justice *et al*. 2002; Wright *et al*. 2002).

As with all sensors, the MODIS system has a number of advantages as well as constraints. Firstly, the high temporal frequency of the MODIS sensor alongside its deployment on two platforms means that there is a global acquisition of data up to 4 times daily (Harris *et al*. 2000; Flynn *et al*. 2002). This particular utility has been recognised and harnessed by the volcanological community with a number of algorithms developed to identify and assess thermal anomalies in near real-time, further discussed in Section 2-5-2 (pg. 51) (Wright *et al*. 2002; Wright *et al*. 2004; Vaughan and Hook 2006; Koeppen *et al*. 2011; Lacava *et al*. 2011). However, as a result of this high overpass frequency, the spatial capabilities of the sensor are reduced (Wright *et al*. 2002). The 1 km resolution of the MIR and TIR bands, therefore, means that while MODIS is well suited to map the spatial distribution of volcanic features, detailed analysis of volcanic hotspots is limited (Wright *et al*. 2002; Wright *et al*. 2004). Alongside this, the 1 km swath of each scanning image can result in a hotspot being counted twice at high latitudes and gaps between adjacent swaths around the equator (Wright *et al*. 2002). Although this does result in complete global coverage only being achieved every 2 days issues related to double counting are mitigated by identifying the same sampling period during acquisition (Wright *et al*. 2002). Similarly, the scanning range of the sensor alongside the curvature of the earth creates a bow-tie effect where at nadir angles the length of a swath is 10 km but at off nadir angles the length of a swath is 20 km resulting in increased pixel size and overlapping (Liu 2005; Wen 2008). In terms of the spectral capabilities, the presence of clouds within a MODIS image creates problems (Wright *et al*. 2002). As thermal anomaly detection is based on the difference in detected radiances in the MIR and TIR wavebands, when radiances related to clouds are detected, confusion between thermally anomalous features and cold clouds occurs resulting in false alarms or missed detections (Wright *et al*. 2002; Rothery *et al*. 2005). Recognising this, many of the algorithms developed for use with MODIS data incorporate a detection threshold to combat the issues related to false alarms and missed detections (Kaufman *et al*. 1998; Hawbaker *et al*. 2008).

2-5-2 MODIS THERMAL ANOMALY DETECTION ALGORITHMS

Recognising the advantages of MODIS to monitor volcanic activity in near real-time, a variety of algorithms have been developed to enable the detection, tracking and analysis of volcanic thermal anomalies, Figure 2-25. In particular, there are three main categories of detection algorithms: contextual (spatial), temporal and fixed threshold (spectral) (Steffke and Harris 2011). By comparing an individual pixel's radiance to surrounding pixels, contextual algorithms apply a flexible threshold based on surrounding characteristics (Steffke and Harris 2011). Originally developed for use with AVHRR data, VAST (Volcanic Anomaly SofTware) is an example of a contextual algorithm that works by comparing the temperature of the target pixel to the average temperature of the surrounding 8 pixels to identify a hotspot (Harris *et al*. 1995; Higgins and Harris 1997; Steffke and Harris 2011). Further work has since adapted this algorithm to process GOES and MODIS imagery for local and regional monitoring of volcanoes (e.g. Harris *et al*. 2000; Vicari *et al*. 2009).

FIGURE 2-25 VOLCANIC HOTSPOT DETECTION ALGORITHMS (SOURCE: STEFFKE AND HARRIS 2011: 1112).

The Robust Satellite Technique (RST, previously RAT) is an example of an algorithm that monitors temporal variations to detect volcanic thermal hotspots (Tramutoli 1998; Di Bello *et al*. 2004; Pergola *et al*. 2008; Lacava *et al*. 2010). In contrast to contextual and fixed threshold algorithms, this technique assesses the change in pixel temperature through time to minimise the effect of geographical and seasonal variations and identify diversions from 'normal' temperature (Marchese *et al*. 2006; Steffke and Harris 2011). Similarly to VAST, this algorithm was originally developed for use with AVHRR data, however, it has since been revised and adapted for a variety of sensors, including MODIS (Pergola *et al*. 2008; Marchese *et al*. 2010). Despite its clear advantages to identify hotspots based on local pixel characteristics, however, the processing associated with this algorithm means that it is not appropriate to monitor volcanic thermal anomalies at a global scale (Marchese *et al*. 2001; Steffke and Harris 2011). In addition, in applying this technique to examine the presence of land surface temperature anomalies prior to the 2001 Gujarat earthquake (India), Blackett *et al*. (2011) identified significant biases due to cloud cover and data gaps in the imagery.

Of particular interest to this thesis, the MODVOLC algorithm (further discussed in Section 2-5-3) is a fixed threshold algorithm developed by the Hawai'i Institute of Geophysics and Planetology (HIGP) (Wright *et al.* 2002). Designed to assess individual target pixels to identify anomalous behaviour, MODVOLC passively monitors 1,500 potentially active volcanoes for elevated temperatures on a daily basis (Kaufman *et al*. 1998; Wright *et al*. 2002; Wright and Pilger 2008). In contrast to the localised thresholds of other volcanic hotspot detection algorithms, however, the MODVOLC threshold is set at a suitably high level so as to enable detections at a global scale with minimum false alarms (Wright *et al*. 2002; Wright *et al*. 2004).

Finally, recognising the specific advantages and limitations of these algorithms, a series of new hybrid algorithms (or, dual-band techniques) have been developed that incorporate different aspects of contextual, temporal and fixed threshold techniques (Steffke and Harris 2011). Such examples of these algorithms include MODVOLC 2 (Koeppen *et al*. 2011), the Okmok algorithm (Dehn *et al*. 2000), MOLDEN (Kervyn *et al*. 2006; Vaughan *et al*. 2008), RSTvolc (Lacava *et al*. 2011) and MYVOLC (Hirn *et al*. 2008). MODVOLC 2, for example, provides an extension to MODVOLC by incorporating the time-series analysis used in the RST algorithm (Koeppen *et al*. 2011). This new approach was found to be capable of detecting up to 15% more thermal anomalies than MODVOLC and, in addition, was more sensitive to low temperature thermal anomalies (Koeppen *et al*. 2011).

Overall, comparisons of these algorithms to 6 case study areas by Steffke and Harris (2011) showed that each algorithm has different advantages. In particular, the RST and VAST algorithms perform more efficiently at a regional and local scale due to their ability to set localised thresholds for detection, whilst the MODVOLC algorithm is more suitably placed to conduct assessments of volcanic activity at a global scale. In addition, while the hybrid algorithms demonstrated the ability to combine specific processing techniques from each of these systems, these algorithms cannot be applied at a global scale for operational monitoring. Therefore, with the view to examine earthquake-volcano interactions at a global scale, it is apparent that MODVOLC is the most appropriate algorithm to monitor the thermal response of volcanoes to earthquakes (Section 2-3-6, pg. 34).

2-5-3 The MODVOLC Algorithm

With regards to this thesis, the MODVOLC algorithm developed specifically for use with data from the MODIS sensor is suitably placed to monitor volcanic activity at a global scale. This algorithm, in particular, operates under minimal processing requirements analysing Level 1B MODIS data to disseminate thermal anomaly alerts based on 4 mathematical operations, Figure 2-26 (Flynn *et al*. 2002; Wright *et al*. 2002; Wright *et al*. 2004).

Acting as a near real-time detection system, MODVOLC provides a proxy for volcanic activity determining the presence of anomalous pixels based on their radiant emissions in the MIR (Band 22(21), 3.959 μm) and TIR (Band 32, 12.02 μm) wavebands where the amount of radiance in the MIR waveband is significantly higher than the detected radiances in the TIR waveband (Wright *et al*. 2002; Wright and Flynn 2003; Wright *et al*. 2004; Wright and Pilger 2008):

Eq. 2-4

Where, B_{22} refers to the spectral radiance (W m^{-2} sr^{-1} μm^{-1}) in MODIS Band 22 and B_{32} refers to the spectral radiance (W m^{-2} sr^{-1} μm^{-1}) in MODIS Band 32. If Band 22 is saturated (temperature exceeds 340 K), radiance from the equivalent Band 21 is used (Flynn *et al*. 2002; Wright *et al*. 2002; Wright *et al*. 2004).

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Figure 2-26 Flow diagram illustrating the mathematical operations executed by the MODVOLC algorithm (Source: Wright *et al*. 2002: 10).

As discussed in Section 2-5-2, rather than defining a calculated threshold that must be exceeded to identify anomalous pixels, the detection of thermal hotspots using MODVOLC is based on a global Normalised Thermal Index (NTI) (Kaufman *et al*. 1998; Wright *et al*. 2002; Wright and Pilger 2008). In order to rapidly identify thermally anomalous features whilst limiting the number of false alarms, a global NTI of -0.80 (night-time threshold) must be exceeded for a pixel to be classed as anomalous (Flynn *et al*. 2002; Wright *et al*. 2002; Wright *et al*. 2004). This threshold, in particular, has been defined based on the analysis of various thermal features (Figure 2-27) and volcanic centres (Figure 2-28) (Wright *et al*. 2002; Wright *et al*. 2004).

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FIGURE 2-27 NORMALISED THERMAL INDEX (NTI) FOR THE MODVOLC ALGORITHM AS DEFINED BY NIGHT-TIME RADIANCES OF THERMAL FEATURES, RED LINE INDICATES THE GLOBAL NTI (ADAPTED FROM: WRIGHT *ET AL*. 2004: 33).

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FIGURE 2-28 EXAMPLE OF NTI HISTOGRAM FOR DETECTED MODIS RADIANCES AT BIG ISLAND, HAWAI'I; ALL PIXELS WITH NTI≥-0.80 CONTAIN ACTIVE LAVA (SOURCE: WRIGHT *ET AL*. 2002: 6).

Although this fixed global threshold has been shown to behave appropriately to monitor a range of volcanic thermal features, a number of studies (e.g. MODVOLC 2 and MODLEN) have demonstrated the reduced sensitivity of the algorithm to low-level or small-scale thermal anomalies and at differing latitudes due to changes in pixel size (Wright *et al*. 2002; Wright and Flynn 2004; Wright *et al*. 2004; Kervyn *et al*. 2006; Vaughan and Hook 2006; Wright and Pilger 2008; Koeppen *et al*. 2011). In addition, the algorithm itself does not discriminate between different thermal features (Wright *et al*. 2002). Therefore, a wildfire within close proximity to a volcanic centre could be misidentified as a volcanic hotspot. More recently, the MODVOLC algorithm has been extended to examine day-time radiances; however, due to the limitations associated with solar contamination (Kaufman *et al*. 1998; Flynn *et al*. 2002; Wright *et al*. 2002; Wright and Flynn 2004), only night-time radiances are used in this research. Finally, despite the MODVOLC algorithm acting as a tool to rapidly identify thermal anomalies, it does not provide a means to quantify the intensity, or radiant flux, of the detected anomaly (Wright *et al*. 2002).

2-5-4 DETERMINATION OF VOLCANIC RADIANT FLUX

Following the determination of anomalous pixels, the quantification of radiative energy emissions from each hotspot is a crucial step in order for the data to be of practical utility. The empirical relationship between anomalous pixels (Band 22(21), 3.959 μm) and ambient surrounding pixels (Band 32, 12.02 μm), therefore, allows methods to be developed which indicate the volcanic radiant flux, or radiative power, of detected thermal hotspots (Kaufman *et al*. 1998). The MIR Brightness-Temperature method developed by Kaufman *et al*. (1998) converts the radiances of detected thermal hotspots as emitted by the MIR and TIR wavebands, first, to temperature using Planck's blackbody radiation law and then to radiative power:

Eq. 2-5

Where, = radiant flux (MW), = brightness temperature at 3.959 μm and = brightness temperature of surrounding (background) ambient pixels (Kaufman *et al*. 1998). However, as the MODVOLC algorithm does not retrieve radiances for surrounding ambient pixels, Wright and Flynn (2004) showed that MODIS Band 32 (12.02 μm) can be used as a proxy for background temperature. More precisely, the lowest Band 32-derived temperature for each month can be used to minimise contamination by thermally anomalous hotspots and compensate for seasonal variations (Wright and Flynn 2004). Although this method has been used extensively to estimate background temperatures, more recently, Wright *et al*. (2014) reported that an independent estimate of surrounding ambient temperature from the MODIS LST (Land Surface Temperature) product is more appropriate than estimated temperatures using Band 32 data which are contaminated by lava and the effect of clouds.

Another method that can be used to quantify the radiant flux of thermally anomalous MODIS pixels is the MIR Radiance method developed by Wooster *et al*. (2003). Here, the MIR radiance and MIR background radiance are converted to radiative temperature (based on Planck's blackbody radiation law), which is then used to calculate radiative energy by assuming a linearly proportional relationship (Wooster *et al*. 2003; Wright and Pilger 2008):

Eq. 2-6

Where, FRE_{MIR} = fire radiative energy (W), L_{MIR} = MIR spectral radiance of the thermally anomalous pixel (W m^{-2} sr^{-1} μm^{-1}) and $L_{MIR,bg}$ = MIR spectral radiance of surrounding background pixels (W m^{-2} sr^{-1} μm^{-1}). In particular, the application of this method allows a time-integrated estimate of radiative energy emitted by a thermal hotspot at the time of satellite overpass, therefore, allowing changes in the behaviour of a volcanic surface to be assessed (Wright and Pilger 2008).

While the application of both of these methods allows the radiant flux of a thermally active volcano to be estimated, the MIR Brightness-Temperature method is used here due to its higher accuracy for radiative hotspots. In particular, the MIR Brightness-Temperature method was designed specifically for the MODIS sensor and has an estimated error for radiative power estimates (500-1,200 MW) of less than 10% (Kaufman *et al*. 1998) whereas the MIR Radiance method has an associated uncertainty of ±30% for MODIS pixel temperatures between 600-1,500 K (Wooster *et al*. 2003).

2-5-5 VOLCANIC ACTIVITY ASSESSMENTS

In applying these methods, a number of studies have now demonstrated the operational utility of satellite remote sensing as well as the ability to monitor the onset and progression of volcanic activity. Wright and Flynn (2004) and Wright and Pilger (2008), for example, show the use of the MIR Brightness-Temperature method and the MIR Radiance method, respectively, to analyse MODVOLC detected radiative power emissions of all thermally active volcanoes, Figure 2-29, identifying Kilauea, Hawai'i; Mount Etna, Italy; Nyamuragira, Democratic Republic of Congo and Piton De La Fournaise, Réunion to be the most thermally radiant volcanoes.

FIGURE 2-29 DAILY RADIATIVE POWER EMISSIONS FROM THE 45 THERMALLY ACTIVE VOLCANOES, 2001-2002. TWO DISTINCT TRENDS CAN BE IDENTIFIED, A STEADY LEVEL OF BACKGROUND ACTIVITY AND SHORT-TERM PERIODS OF INCREASED ACTIVITY DURING LARGE ERUPTIONS, ALSO NOTED BY WRIGHT AND PILGER (2008) (SOURCE: WRIGHT AND FLYNN 2004: 189).

Alongside these global assessments, a number of studies have detailed the use of MODIS data, namely MODVOLC, to examine the thermal behaviour of individual volcanoes. In assessing the thermal activity of Stromboli, Italy, Coppola *et al*. (2012), was able to relate changes in the magma column to variations in activity. In this way, Coppola *et al*. (2012) surmised that by using data from the MODVOLC system changes in activity, or precursors, could be identified to aid forecasting, a factor also discussed by Wright and Flynn (2003) and Bredmeyer *et al*. (2011).

Importantly, one of the advantages of satellite remote sensing is the ability to obtain information on volcanoes that do not require regular ground-based monitoring or are particularly remote. Flynn *et al*. (2002), in particular, documented new activity following thermal anomaly detections at Erta Ale, Ethiopia (Figure 2-30) and Howard Island. Wright *et al*. (2004) also recorded activity at Mount Belinda, Montagu Island, a volcano that had no previously recorded activity during the Holocene.

The ability to compare volcanoes of different eruption styles is another advantage of volcanic remote sensing. Both Wright and Flynn (2004) and Wright and Pilger (2008) suggest that by analysing the thermal flux of volcanoes, variations in eruption intensity and different eruption styles can be compared. A further example demonstrated by Wright *et al*. (2005) and Bredmeyer *et al*. (2011) is the ability to correlate different eruption phenomena to changes in thermal activity. Wright *et al*. (2005), for example, use MODIS alongside EP TOMS (Earth Probe Total Ozone Mapping Spectrometer) and AIRS

(Atmospheric Infrared Sounder) data to analyse ash and thermal emissions before, during and after the eruption of Anatahan, Mariana Islands.

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FIGURE 2-30 MODVOLC THERMAL ANOMALY DETECTIONS AT ERTA ALE, ETHIOPIA MAY 1ST 2001 (SOURCE: FLYNN *ET AL*. 2002: 59).

Overall, the application of satellite remote sensing to monitor changes in volcanic activity demonstrates a crucial avenue in the near real-time monitoring of volcanic activity. Based on this, in context to the study of earthquake-volcano interactions, it is possible to identify changes in volcanic radiant flux following an earthquake to positively identify a response (detailed in Section 2-3-6, pg. 34).

2-6 THE NEED FOR FURTHER RESEARCH

This literature review has provided an account of the current understanding of earthquake-volcano interactions as well as identifying the main challenges faced by researchers; satisfying Objective 1 of this thesis. In particular, it is apparent that the availability of remotely sensed data for volcanology can reduce the constraints of previous research that used historic or observational data. Consequently, research is required to address the effective use of remotely sensed data for earthquake-volcano investigations and establish appropriate methods for analysis. Furthermore, the use of a multi-parameter analysis is needed to examine the various earthquake and volcano characteristics that may affect a response, a factor that has been recognised by previous literature but is yet to be implemented.

Although there is a wide body of research that has investigated earthquake-volcano interactions, it is evident that the relationship is still not clearly understood due to differing responses of individual volcanoes and sub-regions. To gauge the effect of the relationship within different regions, cases of apparent triggering will be compared to volcanoes with no triggering to identify favourable conditions for response. In essence, this would allow the influencing parameters within a system to be identified and, as a result, the potential for response to be determined.

Following from this, a further requirement for future research is to evaluate the effect of each proposed mechanism on different earthquake-volcano interactions. Specific examples of the complexity of the relationship detailed in Section 2-3 (pg. 14), in particular, demonstrate the possibility that differing earthquake and volcano characteristics could cause different physical changes that result in a response over a range of temporal and spatial scales. Indeed, the latter half of Section 2-3 showed the range of factors that may affect a response and demonstrated the challenges in inferring their influence.

Overall, this literature review has emphasised an underlying agreement of a relationship between earthquakes and volcanoes. Gaps in understanding and knowledge of tectonic processes, however, have limited each research group's ability to infer a mechanism for response. With the increasing risk posed by volcanic hazards, the potential benefits of this research to identify precursors to volcanic activity mean that it is essential that further research continues to understand and interpret the relationship between earthquakes and volcanoes. Nevertheless, a reoccurring issue identified throughout this review has demonstrated the need for instrumental measurements to allow for reliable and robust results. Thus, the recognition of multi-parameter investigations rather than statistical analyses of individual earthquake and eruption characteristics, would allow a set of common factors that contribute towards the relationship to be established. The following chapter will now detail the methods used in this research to examine the proposed relationship at a regional and global scale as well as the selection criteria employed to ensure only responses with a true association to an earthquake trigger are assessed.

CHAPTER 3

OBSERVATIONS OF EARTHQUAKE-VOLCANO INTERACTIONS: METHODOLOGY

This chapter details the methods applied in this research to identify changes in volcanic activity following a seismic event and assess possible causative relationships. Following a review of the factors that have been suggested to influence triggering, it is apparent that depending on each research group's selection criteria, each has obtained differing results. Particular focus, therefore, is placed on identifying the favourable conditions that may influence a volcano's response to allow the triggering mechanisms identified in Section 2-3-7 (pg. 37) to be evaluated. As such, this chapter will first outline the methods used to calculate volcanic radiant flux and establish baselines of volcanic activity. Further analysis will then be conducted at two spatial scales; a global assessment to examine the temporal coincidence of increases in global volcanic radiant flux and global seismic energy and a regional assessment to identify and analyse individual earthquake-volcano interactions. Based on this, statistical analyses and machine learning approaches will be employed to identify the parameters that may control a response and assess the use of earthquakes as a precursory indicator to volcanic activity.

3-1 VOLCANIC AND SEISMIC DATASETS

3-1-1 MODVOLC

MODVOLC is a non-interactive algorithm that detects and monitors infrared radiation emitted by erupting volcanoes providing a global inventory of volcanic radiant flux data since 2000 (Wright *et al*. 2002; Wright *et al*. 2004). For those volcanoes identified to be active by the Smithsonian Global Volcanism Program (GVP), MODVOLC data was obtained from the Hawai'i Institute of Geophysics and Planetology (HIGP 2015) to identify all volcanoes that exhibited thermally anomalous behaviour, 2000-2012.

Despite the limitations detailed in Section 2-5-3 (pg. 53), MODVOLC was confirmed as the most suitable algorithm for the assessment of earthquake-volcano interactions. In particular, comparisons to the MODIS Thermal Anomaly Product (MOD14) demonstrated that despite its increased sensitivity to low-intensity hotspots, MOD14 detects significantly fewer thermal anomalies (particularly within coastal or thermally heterogeneous environments) than MODVOLC, Figure 3-1a (Blackett 2009; Thorsteinsson *et al.* 2011; Hill-Butler 2012). Further analysis of these detections demonstrated that MOD14 functions by comparing an anomaly to surrounding pixels and in instances where these pixels are cloud or water; they are excluded from further analysis (Justice *et al.* 2002; Giglio 2010). Alongside this, it was identified that the high sensitivity of MOD14 meant that an anomaly must have a significantly high temperature to be detected (Blackett 2009). Comparisons of calculated volcanic radiant flux, therefore, identified that in instances where there were high background signals, a volcanic hotspot would observe a lower radiant flux than identified by MODVOLC, Figure 3-1b. Based on this, it can be concluded that MODVOLC is the most appropriate algorithm to reliably detect and assess all thermal anomalies.

There are, however, a number of constraints to consider during the assessment of earthquake-volcano interactions. The use of a global NTI (to prevent false alarms), in particular, results in missed detections and insensitivities to low-intensity volcanic phenomena (Wright *et al*. 2002; Wright *et al*. 2004; Wright and Flynn 2004; Wright and Pilger 2008). While alternative algorithms that use a local threshold (e.g. MODLEN and the Hybrid approach) to improve detection sensitivity exist, they are not currently developed for all volcanoes for use as a near real-time monitoring tool (Kervyn *et al*. 2006; Vaughan *et al*. 2008; Giglio 2010; Koeppen *et al*. 2011). As discussed in Section 2-5-3, this research will only use night-time MODIS detections. Whilst the inclusion of day-time imagery would improve the sampling frequency by up to 50% in some locations and reduce the risk of missed detections for short-term volcanic features, only night-time data is used to limit the number of false alarms due to contamination by reflected sunlight and solar heating. Cloud within a MODVOLC scene also causes issues obstructing thermal hotspots resulting in missed detections or causing false alarms due to confusion with active lava pixels, Figure 3-2 (Wright *et al.* 2002; Wright *et al.* 2004; Wright and Pilger 2008). Finally, the absence of imagery in the MODVOLC database means that the source of the thermal hotspot cannot be determined and the role of atmospheric clouds or volcanic ash cannot be assessed (Wright *et al.* 2002; Wright *et al.* 2004; Wright and Pilger 2008). Despite this, comparisons to manual inspections of MODIS scenes have reported accuracies of more than 80% for the detection of high intensity thermal anomalies using MODVOLC (Steffke and Harris 2011).

A

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FIGURE 3-1 COMPARISON OF MODVOLC AND MOD14 RADIANT FLUX DETECTIONS - A) COMPARES DETECTED THERMAL ANOMALIES AND B) COMPARES THE MAGNITUDE AND TEMPORAL DYANMICS OF MODVOLC AND MOD14 DETECTIONS. EXAMPLE BASED ON A PERIOD OF THERMAL UNREST AT PUYEHUE-CORDÓN CAULLE, CHILE 2011.

FIGURE 3-2 CONFUSION BETWEEN 'COLD' CLOUD PIXELS AND ACTIVE LAVA PIXELS (IDENTIFIED IN RED CIRCLES) IN MODIS BAND 22(21)-32 VALUES. EXAMPLE SHOWN FOR PERIOD OF THERMAL ACTIVITY AT BIG ISLAND, HAWAI'I 02/02/2001 (ADAPTED FROM: WRIGHT *ET AL*. 2002:6).

3-1-2 MODIS LAND SURFACE TEMPERATURE (LST) PRODUCT

The MODIS Global Land Surface Temperature (LST) and Emissivity product provides data on the average temperature of land-only pixels during an 8-day period (Wan 2013). The current MODIS LST product (version 6) has been shown to be accurate up to 1 K (in most cases) as well as accounting for the previous miscalculations related to cloud contamination observed by Blackett (2009) (Wan 2008; Wan 2014). For this research, the LST product was used to provide an estimate of surrounding ambient temperatures (Wright *et al*. 2015). Data was obtained (from the analysis of MOD11 [Terra MODIS] and MYD11 [Aqua MODIS] files) for each volcano identified to be active by MODVOLC based on a 1-pixel extent and screened for cloud, 2000-2010 (Wright *et al*. 2014).

3-1-3 USGS SEISMIC CATALOGUE

The United States Geological Survey National Earthquake Information Centre (USGS NEIC) maintains an archive of all seismic events occurring worldwide and is currently reliable for all M≥4.5 earthquakes at a global scale (USGS 2015). Data on the time, location, depth and magnitude of all earthquakes (M≥4.5) that occurred globally were obtained for the period 2000-2012 (accessed 12/08/2013). In order to reflect the 731-day assessment window (in which change in activity is calculated based on the difference in thermal unrest 365 days preceding and following an earthquake detailed in Section 3-4-2-1, pg. 74) only earthquakes that occurred 2001-2011 were assessed. In the global analysis, the temporal coincidence of global seismic energy release (all M≥4.5

earthquakes) as compared to global volcanic radiant flux was assessed. To examine the ability of large magnitude earthquakes to affect volcanic activity at a global scale (e.g. West *et al*. 2005; Lemarchand and Grasso 2007), all M≥8.0 events were also analysed individually. In the regional assessment, all significant earthquakes (M≥6.0) were examined in order to analyse the role of M≥6.0 earthquakes in influencing activity within a regional setting (e.g. Manga and Brodsky 2006; Eggert and Walter 2009).

3-1-4 Global CMT Catalogue

Earthquake focal mechanisms were obtained from the Global Centroid-Moment-Tensor (CMT) Project (Dziewonski *et al*. 1981; Ekström *et al*. 2012). The Global CMT Project maintains a catalogue of seismic moment tensors from 1976 and provides a representation of an earthquake's point-source CMT including information on its strike and dip (Ekström *et al*. 2012). The CMT catalogue is currently complete for all M≥5.2 earthquakes (from 2004 onwards, previously M≥5.4) making it appropriate to provide data for all M≥6.0 earthquakes analysed in this research (Ekström *et al*. 2012). Data for each triggering earthquake identified in the regional assessment of this study was obtained in order to understand the pattern of radiated energy.

3-1-5 Smithsonian Global Volcanism Program

The Smithsonian GVP documents information about global volcanic activity within the Holocene (*c*. 10,000 years) (Smithsonian Global Volcanism Program 2015). While the GVP database is still not complete, a number of revisions have been made to the database in recent years to conduct quality checks and ensure the completeness of eruption records (Venzke 2015). Data including a volcano's eruptive history, geographic location, volcano type and geological setting were obtained for each volcano identified to be active by MODVOLC, 2000-2012.

3-1-6 ESRI Online Datasets

ESRI develops and maintains a variety of online datasets including information on the Earth's surface (ESRI 2015). Data on the tectonic setting and plate boundaries for each earthquake-volcano interaction in the regional assessment were derived from information provided by the USGS and obtained from ESRI's online database (ESRI Canada 2012).

3-2 MIR BRIGHTNESS-TEMPERATURE METHOD

As identified in Section 2-5 (pg. 48), there is a need to convert radiances, as extracted by the MODVOLC algorithm, to radiant flux for the data to be of quantitative utility. In total once only volcanic-attributable data were extracted (i.e. all volcanoes were manually checked to identify hotspots within a volcano's geographic location), thermal anomalies were detected at 99 volcanoes. To be able to calculate the radiant flux of all anomalous pixels, the thermal radiance as detected by MODIS Band 22 (or 21, if temperature exceeds 340 K) was first converted to temperature using Planck's Blackbody Radiation Law (Eq. 2-2, pg. 48).

For instances where Band 22 were exceeded (if temperature exceeds 340 K), Band 21 was used and in instances where both Bands 22 and 21 (if temperatures exceed 500 K) were saturated the maximum measurable spectral radiance was used. For Terra MODIS the maximum measurable limit is 60 W m^{-2} sr^{-1} μm^{-1} and for Aqua MODIS this value is 93 W m^{-2} sr^{-1} μm^{-1} (Wright *et al*. 2014). In total, saturation of both Bands 22 and 21 occurred at 7 volcanoes (Etna, Italy; Fernandina, Ecuador; Llaima, Chile; Nyamuragira, Democratic Republic of Congo; Nyiragongo, Democratic Republic of Congo; Piton De La Fournaise, Réunion and Tolbachik, Russia) in detections using Terra MODIS and accounted for less than 0.5% of the total number of detected hotspots for each volcano.

In order to compare anomalous pixels to surrounding ambient surface temperatures to identify anomalous activity (discussed in Section 2-5, pg. 48), a value for background temperature was determined using the MODIS LST product (Wright *et al*. 2014). Previously, radiances derived from MODIS Band 32 (12.02 μm) have been used as a proxy for surrounding ambient temperatures (e.g. Wright and Flynn 2004), however, contamination of spectral radiances from volcanic hotspots returned anomalously high radiant flux values (as discussed in Section 2-5-4, pg. 56). For example, using MODIS Band 32 values the total radiated flux at Erebus, Antarctica was 257,987 MW for the study period (2000-2012) whereas using the LST product the total flux radiated for the period was notably lower, 226,928 MW. As a result, recorded LST temperatures (Section 3-1-2, pg. 64) were averaged to provide an independent estimate of background temperature for each calendar month and each volcano under assessment. In addition, to minimise contamination by solar radiance, only night-time data or data with an associated solar zenith greater than 95° were considered (Flynn *et al*. 2002).

Using the MIR Brightness-Temperature method (Kaufman *et al*. 1998), these temperatures were then converted to radiant flux for each volcano:

Eq. 3-1

Where = radiant flux (MW), = hotspot pixel temperature converted from MODIS Band 22 (or 21, if temperature exceeds 340 K) and = surrounding ambient pixel temperature estimated from the MODIS LST product (Kaufman *et al*. 1998).

3-3 ESTABLISHING BASELINES WITHIN VOLCANIC RADIANT FLUX

In order to recognise changes from their 'normal' thermal state, an assessment of a volcano's long-term behaviour must be conducted. Currently, however, no common method exists which can establish baselines of volcanic activity (Phillipson *et al*. 2013). In view of this, the preliminary stage of this research aimed to determine the normal variability (baseline) within volcanic radiant flux against which changes in flux could be compared to identify their significance.

Overall, six approaches to identify baselines within volcanic radiant flux were examined. A key concern, however, was to achieve the most representative method to measure normal variability. In particular, it must be remembered that volcanoes can exhibit varying levels of activity. For example, a volcano may be persistently active with on-going low-level activity or a volcano could experience intermittent periods of high-level explosive activity. Therefore, each of the six approaches were examined based on volcanic radiant flux data from 6 volcanoes with varying levels of activity (Figure 3-3). In addition, a number of temporal windows were examined, further discussed in Section 3-4-2-1.

1) Monthly average volcanic radiant fluxes were calculated for each volcano (Figure 3-4). This involved calculating the average volcanic flux for each calendar month and comparing it to daily volcanic radiant flux. Although this may be appropriate to establish baselines within climate data, the application of this method to volcanic activity data is limited due to the high variability of volcanic behaviour and limited evidence of cyclicity (Sparks and Aspinall 2004; Manga and Brodsky 2006). For persistently active volcanoes like Bagana, for example, high radiant flux detections in the preceding month could mask significant changes in renewed activity on a given day.

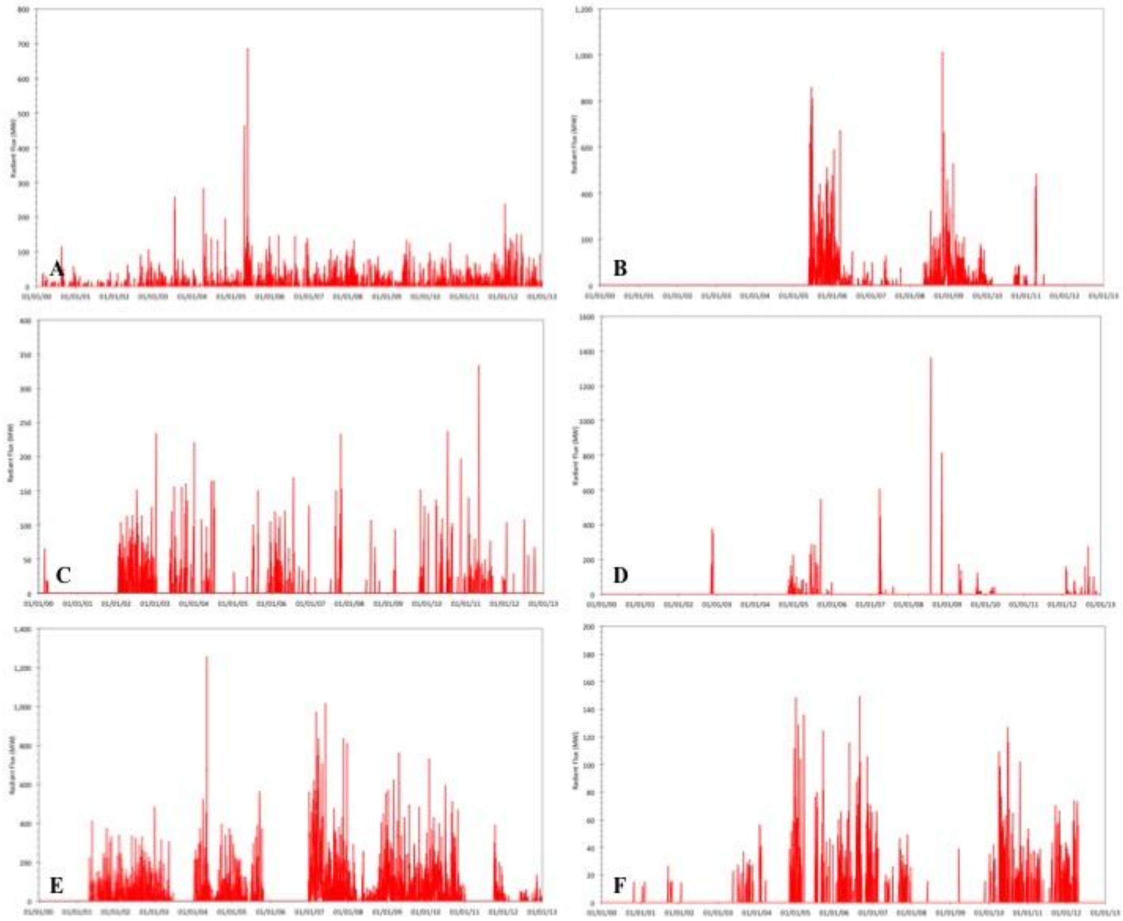


FIGURE 3-3 VOLCANOES THAT EXHIBIT VARYING LEVELS OF ACTIVITY EXAMINED AS PART OF THE ASSESSMENT OF BASELINES WITHIN VOLCANIC RADIANT FLUX, A) BAGANA, PAPUA NEW GUINEA; B) BARREN ISLAND, INDONESIA; C) KARYMSKY, KAMCHATKA; D) REVENTADOR, ECUADOR; E) SHIVELUCH, KAMCHATKA; F) VILLARRICA, CHILE (RED LINES INDICATES VOLCANIC RADIANT FLUX).

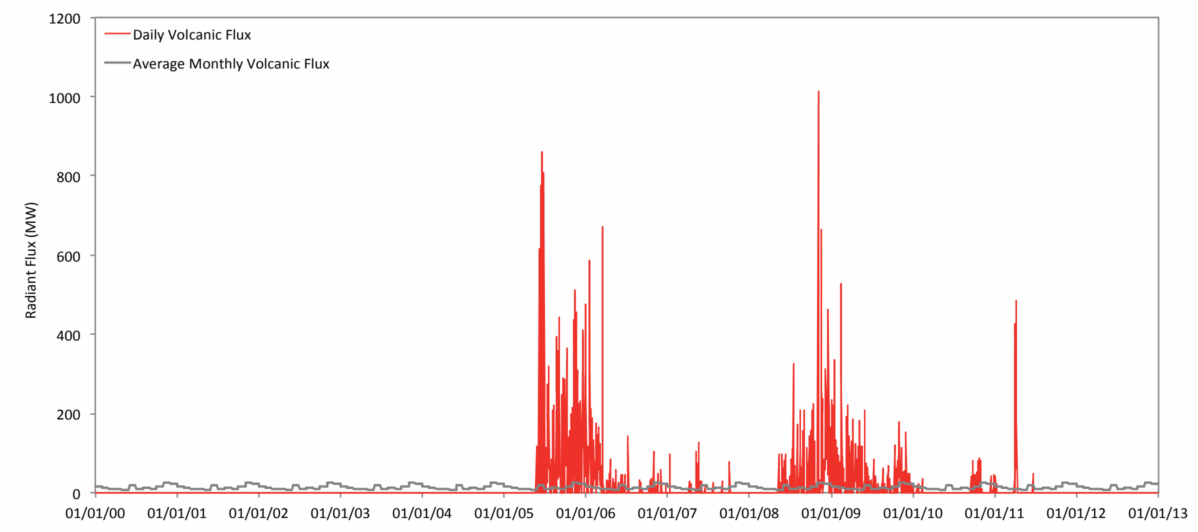


FIGURE 3-4 DAILY VOLCANIC RADIANT FLUX AS COMPARED TO AVERAGE MONTHLY VOLCANIC FLUX (APPLIED TO VOLCANIC RADIANT FLUX DETECTIONS AT BARREN ISLAND, INDONESIA).

2) Constant moving window approach to assess whether activity in the preceding 90-day period[1] was a reliable indicator of significant changes in volcanic activity on a given day. In this approach, the average radiant flux plus 1-standard deviation was compared to the daily volcanic flux, 2000-2012 (Figure 3-5a). While this approach identified anomalous periods of activity, its application in the long-term would present a number of issues for volcanoes with intermittent or latent activity (e.g. 90% of cases tested classified changes in volcanic radiant flux as anomalous when a volcano previously experienced low-level or latent activity).

Other such approaches that presented increased sensitivities to volcanoes with intermittent or latent activity were:

3) 90-day constant moving window using 2-standard deviations – daily volcanic flux compared to radiant flux values 2-standard deviations above the average (Figure 3-5b).
4) 90-day constant moving window accounting for activity in the preceding 90-days – removal of summed radiant flux for the preceding 90-day period from volcanic radiant flux on a given day to identify possible anomalous activity and compare periods of thermal unrest to a 90-day moving window 1-standard deviation above the average (Figure 3-5c).
5) 90-day constant moving window using a 5-day threshold – daily volcanic radiant flux compared to activity in the preceding 90-days, radiant flux values 1-standard deviation above the mean had to be exceeded for at least 5 days for a change to be classed as anomalous (Figure 3-5d).

The final approach assessed the inter-annual variability in daily volcanic radiant flux (Figure 3-6). Using 12 years of volcanic flux data (2000-2012), the average (v) and standard deviation (σ) for each calendar day (where leap years were omitted) was calculated, this enabled a threshold to be established that compared radiant flux values 1-standard deviation above the average ($v + 1\sigma$) of daily volcanic flux (1σ was used rather than 2σ as the 2σ threshold did not identify significant variations in activity at volcanoes with low level thermal activity e.g. Figure 3-4b). On the basis of identifying periods of potentially triggered volcanic activity following an earthquake, change in activity was

[1] A temporal window of 90-days was used as an example

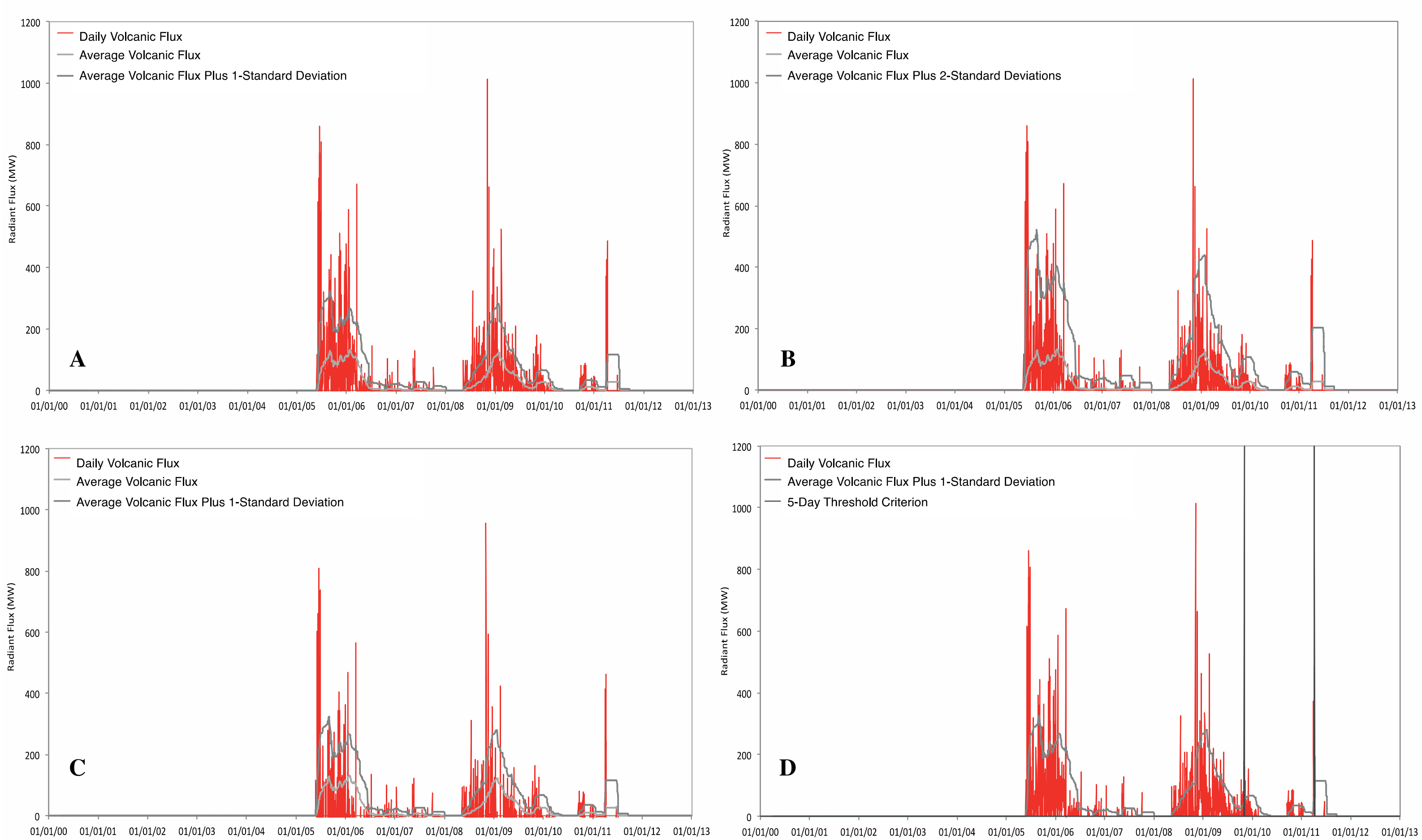


FIGURE 3-5 DAILY VOLCANIC RADIANT FLUX AS COMPARED TO A 90-DAY MOVING WINDOW A) 1-STANDARD DEVIATION ABOVE THE AVERAGE VOLCANIC FLUX, B) 2-STANDARD DEVIATIONS ABOVE THE AVERAGE VOLCANIC FLUX, C) 1-STANDARD DEVIATION ABOVE THE AVERAGE VOLCANIC FLUX AND ADJUSTED FOR THE PRECEDING 90-DAY PERIOD AND D) 1-STANDARD DEVIATION ABOVE THE AVERAGE VOLCANIC FLUX WHERE THE BLACK LINES INDICATE PERIODS WHEN THE 5-DAY THRESHOLD CRITERION WAS MET (APPLIED TO VOLCANIC RADIANT FLUX DETECTIONS AT BARREN ISLAND, INDONESIA).

classed as anomalous when the threshold for inter-annual variability ($v + 1\sigma$) was exceeded for 5 or more daily volcanic flux detections over a 30-day period. A 5-day criterion was identified on the basis of previous research by Hill-Butler (2012) who identified the need to limit false detections and identify erupting volcanoes. Overall, this approach is shown to be particularly appropriate for the assessment of baselines within satellite-derived volcanic radiant flux data as it accounts for any seasonal variations within the satellite data as well as comparing all periods of volcanic flux to identify anomalous activity. As a result, the inter-annual variability in daily volcanic flux ($v + 1\sigma$) was applied to both the global and regional assessments of earthquake-volcano interactions as a threshold to identify possible thermal responses to seismic events. In the global study, each volcano's flux was summed to determine a global value for $v + 1\sigma$. While in the regional assessment, each volcano's $v + 1\sigma$ was calculated.

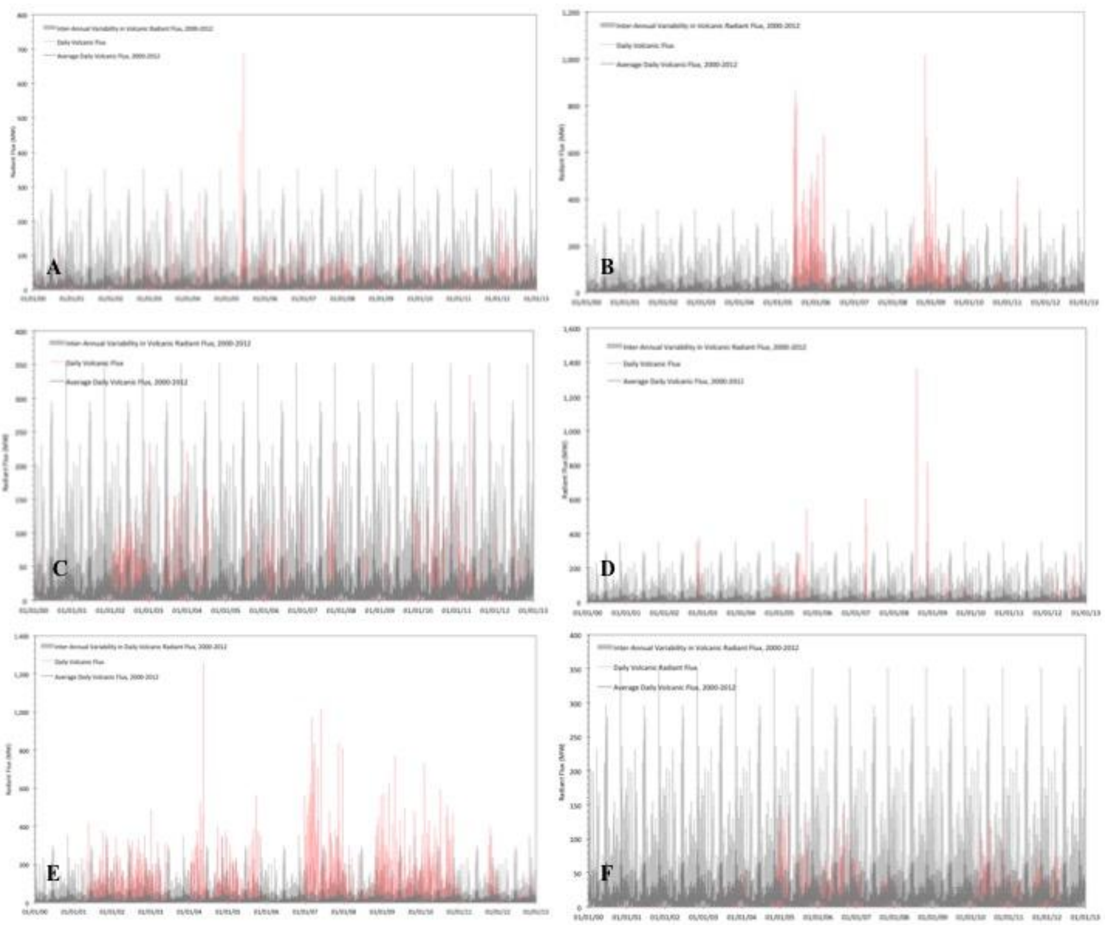


FIGURE 3-6 DAILY VOLCANIC RADIANT FLUX AS COMPARED TO THE INTER-ANNUAL VARIABILITY IN VOLCANIC RADIANT FLUX ($v + 1\sigma$), 2000-2012, A) BAGANA, PAPUA NEW GUINEA; B) BARREN ISLAND, INDONESIA; C) KARYMSKY, KAMCHATKA; D) REVENTADOR, ECUADOR; E) SHIVELUCH, KAMCHATKA; F) VILLARRICA, CHILE.

3-4 ASSESSMENTS OF CAUSATIVE RELATIONSHIPS BETWEEN LARGE EARTHQUAKES AND VOLCANIC ACTIVITY

As detailed in Section 2-3-2 (pg. 16), Linde and Sacks (1998) set out a key method to compare volcanic activity before and after a seismic event. This research is based on an extension of this method using data from the MODVOLC system, a proxy for volcanic activity, as detailed by Harris and Ripepe (2007) and Delle Donne *et al*. (2010) as well as response criteria to identify triggered interactions and assess the thermal response of volcanoes to earthquakes. Volcanic radiant flux was first examined at a global scale to evaluate the global response of volcanoes to earthquakes, particularly large seismic events (M≥8.0). Following this, regional interactions between earthquakes and volcanic radiant flux were analysed to assess the parameters that control a volcano's response.

3-4-1 STUDY 1: GLOBAL VOLCANIC RADIANT FLUX RESPONSES TO EARTHQUAKES, 2000-2012

The MODVOLC-derived radiant flux inventory (Section 3-2, pg. 66) was compared with seismic energy release to assess the global extent of the relationship between earthquakes and volcanic activity. Firstly, the temporal coincidence between cumulative volcanic radiant flux and cumulative seismic energy was examined to assess if changes in volcanic flux correlated with seismic events at a global scale. Cumulative volcanic radiant flux was calculated by summing all radiant flux values for each calendar day. These daily radiant flux totals were then added to provide a cumulative total for the study period. Similarly, cumulative seismic energy was calculated by adding the seismic energy for each M≥4.5 earthquake to provide a daily seismic energy value and the cumulative seismic energy for the period. The seismic energy of each earthquake was calculated:

Eq. 3-2

Where S_e = Seismic Energy (J, Joules) and M = magnitude of the earthquake (M_w, Moment Magntiude) (Gutenberg and Richter 1956).

All large magnitude earthquakes (M≥8.0, 2001-2011) as recorded by the USGS NEIC were then considered over a 731-day window (change in activity ±365 days centred on the earthquake) to examine if large magnitude earthquakes are capable of influencing global volcanic activity as suggested by West *et al*. (2005) and Lemarchand and Grasso (2007). A

731-day assessment window (change in activity ±365 days centred on the earthquake) was employed in order to reflect the time taken for changes within a magma chamber to manifest in an eruption or period of unrest (Hill *et al*. 2002; Cannata *et al*. 2010; Feuillet *et al*. 2011; Jay *et al*. 2013). The daily percentage change in global volcanic flux up to 365 days preceding and following each M≥8.0 earthquake was then analysed to determine whether global volcanic flux was enhanced or inhibited following a large seismic event. For each case, the daily summed volcanic flux ±365 days relative to each earthquake were compared to $v + 1\sigma$ to identify significant changes in global volcanic activity. In addition, frequency histograms (e.g. Linde and Sacks 1998; Manga and Brodsky 2006; Lemarchand and Grasso 2007; Eggert and Walter 2009) showing the average number of erupting volcanoes ±365 days relative to each earthquake (N_b, average number of erupting volcanoes preceding an earthquake and N_a, average number of erupting volcanoes following an earthquake) were examined to assess whether earthquakes changed the number of erupting volcanoes globally (as detected by MODVOLC) as well the volcanic flux. Corresponding β-statistics, a statistical test normally applied in seismology (e.g. Matthews and Reasenberg 1988; Reasenberg and Simpson 1992; Hough 2005; Hill 2007), were also calculated to examine the significance of any association between earthquakes and the number of erupting volcanoes (Walter and Amelung 2007):

$$\frac{\quad}{\quad} \qquad \text{Eq. 3-3}$$

Where = number of erupting volcanoes in the 365 days following an earthquake, = expected number of erupting volcanoes (based on the total number of erupting volcanoes in the 365 days preceding an earthquake) and $_b$ = variance of (Matthews and Reasenberg 1988). As the β-statistic represents the number of standard deviations from which the rate of potential triggering differs from the expected background estimate (Hill 2007), a large and positive β-statistic indicates that the number of erupting volcanoes increased following an earthquake and a negative β-statistic indicates that the number of erupting volcanoes decreased. For this research, an associated β-statistic of ±100 is used to identify a significant change in the number of erupting volcanoes.

3-4-2 STUDY 2: REGIONAL RELATIONSHIPS BETWEEN EARTHQUAKES AND VOLCANIC ACTIVITY

3-4-2-1 PHASE 1 – IDENTIFICATION OF POTENTIALLY TRIGGERED EVENTS

For all volcanoes found to exhibit thermally anomalous behaviour (Section 3-2, pg. 66), all seismic events (as recorded by the USGS NEIC) with a M≥6.0 and within 1,000 km of a volcano's geographic location were identified. Whilst the global assessment considers the influence that large magnitude earthquakes (M≥8.0) have on any interaction between earthquakes and volcanoes, the regional assessment examines tectonic earthquakes with a M≥6.0 due to their ability to affect volcanoes within a regional setting (e.g. Manga and Brodsky 2006; Harris and Ripepe 2007; Eggert and Walter 2009). The 1,000 km regional extent was defined on the basis of previous research findings that suggested potential variability within different regional settings (Section 2-3-2, pg. 16). In particular, Marzocchi *et al*. (2004) (Figure 2-3, pg. 18) indicated that a buffer of 1,000 km was appropriate based on an earthquake's ability to elicit regional responses following a change in stress. Alongside this, Hill *et al*. (2002) stated that significant earthquakes (i.e. M≥6.0) may be capable of inducing faulting up to 1,000 km away. MODVOLC-derived radiant flux was then cross-checked with all M≥6.0 earthquakes to identify potentially triggered volcanic responses. In order for interactions with potentially triggered activity and not temporal coincidences of earthquakes and volcanoes to be identified this research determined a number of criteria that had to be met:

- Change in activity was assessed over a 731-day window (centred on the earthquake), where change in activity was calculated based on the 365 days following an earthquake as compared to the 365 days preceding an earthquake;
- In order to reflect the 731-day assessment window (i.e. change in activity ±365 days centred on the earthquake), volcanic radiant fluxes 2000-2012 were assessed, while seismic events for the period 2001-2011 were analysed;
- Change in volcanic radiant flux had to be at least ±100% to identify significant changes in a volcano's activity;
- $v + 1\sigma$ had to be exceeded for 5 or more daily radiant flux detections over a 30-day period to identify changes from their average volcanic flux (2000-2012); and,
- A volcano's β-statistic had to be at least 100 to infer any significance in the change in the number of days experiencing thermal unrest.

In addition and to aid the identification of earthquake-volcano interactions, a number of conditions as recommended by Hill-Butler (2012) were applied to the assessment of potentially triggered events:

- For the purpose of this research, a volcano had to have a minimum of 5 volcanic radiant flux detections over a 30-day period (i.e. sustained activity) to be defined as an eruption in order to minimise false alarms and misidentification of other thermal activity (e.g. fires);
- Gaps in volcanic radiant flux detections of more than 30 days were classed as separate eruptions;
- For days with multiple radiant flux detections, separate pixels with detected thermal anomalies (based on their MODVOLC-derived Unix Time ID) were summed to provide a total volcanic flux value for that given day; and,
- Earthquakes within a period of potentially triggered volcanic flux and for a minimum of 30 days following that period were not considered to ensure that further periods of 'potentially triggered' activity were not an artefact of previously triggered activity and enable the effect of that individual earthquake to be assessed.

These conditions were applied in this research in order to ensure the most appropriate threshold was used to identify significant changes in activity following an earthquake. As discussed in Section 2-3 (pg. 14), the identification of potentially triggered responses is critical in order to reliably assess the relationship between earthquakes and volcanic activity. While these criteria may be subjective and may not have identified all interactions based on these conditions, it did ensure that volcanoes already experiencing a period of increased flux were not misidentified as 'triggered'. Equally, the minimum number of 5 volcanic hotspot detections over a 30-day window meant that short-lived responses were not identified as triggered. Even though cases of short-lived activity may be just as probable following an earthquake as sustained periods of thermal unrest, the need for response criteria to identify potentially triggered activity means that they are not assessed in this research. Finally, the use of a different assessment window may result in different periods being identified as 'triggered' (Figure 3-7), however, in order to reflect the time for changes within the magma chamber to initiate new activity and reliably infer an earthquake-triggering source a 731-day assessment window (centred on the earthquake) was employed.

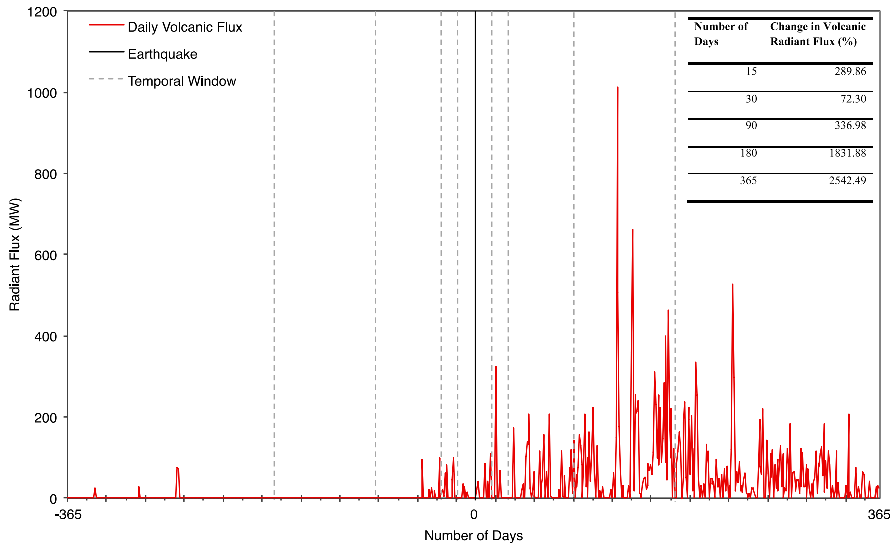


FIGURE 3-7 COMPARISONS OF DIFFERENT ASSESSMENT WINDOWS (± 15, 30, 90, 180 AND 365 DAYS BEFORE AND AFTER AN EARTHQUAKE) ON CHANGE IN VOLCANIC RADIANT FLUX. INSET: % CHANGE IN VOLCANIC RADIANT FLUX BASED ON EACH ASSESSMENT WINDOW (APPLIED TO VOLCANIC RADIANT FLUX DETECTIONS AT BARREN ISLAND, INDONESIA FOLLOWING A M6.6 EARTHQUAKE, 27/06/2008).

Non-response case studies were also identified in order to compare the parameters controlling the relationship between earthquakes and volcanoes. In each case, a non-response interaction was defined on the basis of changes in volcanic activity following an earthquake not meeting the response criteria or in cases where an earthquake occurred within 1,000 km of a volcano but no thermal response was recorded. While it would also be appropriate to analyse events in which a period of increased flux occurred without the existence of an earthquake trigger, for the purpose of the subsequent analysis of event parameters these non-response case studies were removed, as they did not have the parameters related to an earthquake trigger.

3-4-2-2 PHASE 2 – ACQUISITION OF ADDITIONAL VOLCANIC AND SEISMIC DATASETS

For each case of triggered and non-triggered activity, additional volcanic and seismic parameters (as identified by previous research, Table 2-1 pg. 31) related to the triggering earthquake and responding volcano were acquired in order to conduct further analysis of event parameters and determine the conditions that may control any relationship. Table 3-1 details each of the parameters examined in this research along with their proposed influence which were then assessed using statistical analyses and machine learning approaches in Section 3-4-2-3 (pg. 78) (Appendix I identifies the source of each of the parameters examined).

TABLE 3-1 VOLCANIC AND SEISMIC PARAMETERS (INCLUDING PROPOSED INFLUENCE) TO BE USED FOR FURTHER ANALYSIS AS IDENTIFIED BY PREVIOUS RESEARCH (TABLE 2-1, PG. 31).

Parameter	Proposed Influence
Earthquake Magnitude	Earthquake magnitude may influence the level of volcanic response
Earthquake Rupture Length	Zone of earthquake rupture is suggested to have a large influence on the volcanoes that may respond
Earthquake Depth	Variable earthquake characteristics may influence the level and type of response
Earthquake Azimuth to Volcano	The azimuth may indicate the optimum angle between the triggering earthquake and responding volcano for responses to occur
Earthquake Strike	Variable earthquake characteristics may influence the level and type of response
Earthquake Dip	Variable earthquake characteristics may influence the level and type of response
Type of Earthquake Fault	Variable earthquake characteristics may influence the level and type of response
Incoming Earthquake Wave Direction	Volcanoes located in zones of greatest wave energy may be more likely to respond
Region of Earthquake	Variability has been noted between different regions and is thought to influence response
Tectonic Setting of Earthquake's Location	Variability has been noted between different regions and is thought to influence response
Tectonic Plate of Earthquake’s Location	Variability has been noted between different regions and is thought to influence response
Type of Volcanic Response	The status of the volcano at the time of an earthquake may influence whether a response occurs
VEI of Volcanic Activity	The eruption intensity may indicate degree of triggering and variations from normal eruptive activity
Length of Volcanic Response	The length of a volcano’s response may indicate degree of triggering
Time Since Last Period of Volcanic Activity	The time since the last eruption may indicate whether a volcano is in a critical state to respond
Status of Volcano at Time of the Earthquake §	The status of the volcano at the time of an earthquake may influence whether a response occurs
Volcano Type	Type of volcano may define whether a response occurs or the type of response experienced
Magma Composition	A volcano’s chemical composition may control the type and level of response
Surrounding Volcanic Geology	The tectonic setting may influence the level of stress change following an earthquake and, therefore, whether a response occurs
Region of Volcano	Variability has been noted between different regions and is thought to influence response
Tectonic Setting of Volcano's Location	The tectonic setting may influence the level of stress change following an earthquake and, therefore, whether a response occurs

Tectonic Plate of Volcano's Location	Variability has been noted between different regions and is thought to influence whether a response occurs
Type of Crust of Volcano's Location	The tectonic setting may influence the level of stress change following an earthquake and, therefore, whether a response occurs
Temporal Delay Between Triggering Earthquake and Responding Volcano	The delay between triggering earthquake and responding volcano is thought to indicate the state of the volcanic system as well as the effect of other parameters e.g. distance
Distance	Volcanoes at an optimum distance from the earthquake epicentre may be more likely to respond
Location of Volcano in Relation to Earthquake	A volcano's location in relation to earthquake fault rupture is thought to influence whether an increase or decrease in activity would be experienced following a triggering earthquake
Volcanic Compression or Dilatation	Volcanoes located in zones of critical stress change may be more susceptible to triggering following the passage of seismic waves

§ Status of Volcano at the Time of the Earthquake will be classed as latent or active. Although there is no universal classification, in this research active refers to volcanoes that have been active in the year preceding a triggering earthquake and latent refers to volcanoes that have not experienced activity in the year prior to a triggering earthquake.

3-4-2-3 PHASE 3 – STATISTICAL ANALYSES OF EVENT PARAMETERS

Following the identification of potentially triggered events and the acquisition of additional seismic and volcanic parameters, a number of qualitative and quantitative analyses were conducted to assess the significance of the responses identified. While Chapter 2 detailed a number of potential mechanisms that could affect any relationship between earthquakes and volcanic activity, there is no evidence that supports one mechanism in particular. Therefore, to comprehensively evaluate the role of any mechanism on triggering, the parameters suggested to influence the relationship between earthquakes and volcanoes (Table 3-1) were examined rather than assessing each mechanism. As a result, the aim of this stage of the research was to determine whether the parameters within the response and non-response case studies differed as, in such cases, it may be suggested that causative relationships between earthquakes and volcanic activity exist. Crucially, to quantify the effect of each parameter on triggering this stage of the thesis used statistical analyses and machine learning, an approach not before utilised in the assessment of earthquake-volcano interactions, to assess the conditions that influence triggering, identify patterns within the data and assess the predictive utility of earthquakes as a precursor to volcanic activity.

Initially, each parameter (Table 3-1) under study was compared independently to response and non-response case studies. These results provided a qualitative utility allowing the identification of key patterns for each individual parameter and to demonstrate differences in their characteristics as associated with triggered and non-triggered responses. At this stage, the results of decreases in activity following an earthquake were also examined. While these cases of triggered responses may be as common as increased volcanic activity, the methodology employed in this research to identify potentially triggered events only identified 2 instances of decreased activity. As a result, further analysis based on these interactions was not conducted and they are presented to demonstrate this type of response.

The typical response related to increased activity following an earthquake trigger was then examined. This was conducted in two steps: 1) a visual assessment of the change in radiant flux for volcanoes with on-going and new activity and 2) a statistical assessment of the number of days experiencing thermal unrest before and after an earthquake, N_b and N_a. While similar frequency distributions have been examined previously (e.g. Linde and Sacks 1998; Manga and Brodsky 2006; Lemarchand and Grasso 2007; Eggert and Walter 2009; Watt *et al*. 2009), the statistical significance of this change has not been assessed. The average number of volcanoes experiencing thermal unrest on a given day was first calculated for all earthquake-volcano interactions for the complete 731-day assessment window (i.e. change in activity ± 365 days centred on the earthquake). By use of a *t*-test, the change in the number of days experiencing thermal unrest was assessed over the 365-days following an earthquake, N_a, as compared to the 365-days preceding an earthquake, N_b. In addition, to assess if the change in the number of days experiencing thermal unrest, N_b as compared to N_a, was statistically different to all periods where no response was identified following an earthquake, all potentially triggered interactions were compared to the number of days experiencing thermal unrest for all non-responses using the analysis of variance test (ANOVA).

Using the parameters identified for each earthquake-volcano interaction (Table 3-1), CART (Classification and Regression Trees) analyses were performed using machine learning (detailed in Section 2-1, pg. 8) to characterise the parameters influencing the response of volcanoes to seismic events (Breiman *et al*. 1984; BigML 2015). This technique was employed using BigML, an online application of machine learning (BigML 2015). BigML, in particular, uses a modification of the CART algorithm:

Eq. 3-4

to define a binary decision tree based on the parameters within the data. Where y is the objective field (i.e. the field to be predicted), g is the classification or regression model based on whether the objective field is a category (classification) or number (regression), x are the input data (i.e. the earthquake-volcano interaction case studies) and θ are the associated parameters (Breiman *et al*. 1984; Alpaydin 2010; BigML 2015). The resulting trees (example presented in Figure 3-8) identify a hierarchical output that is composed of decision nodes and terminal leaves (Figure 3-9) (Alpaydin 2010; BigML 2015). Each node defines a line of enquiry to identify patterns within the data and terminal leaves represent their result (Alpaydin 2010; BigML 2015). The process starts at the root (input data, x) and grows by adding branches and leaves until a resolution is reached (Figure 3-9) (Alpaydin 2010; BigML 2015). During tree construction, splits (branches) are chosen which cause the largest decrease in error (Alpaydin 2010). BigML implements a streaming histogram that choses splits (currently 64) using information gain, which works to specify the number of instances needed to resolve the model for classification and variance reduction, where the mean square errors measure the goodness of a split for regression (Ben-Haim and Tom-Tov 2010; Alpaydin 2010; BigML 2015). Individual trees may then be pruned by estimating the error at each node and removing sub-trees if they do not improve the prediction to reduce overfitting (BigML 2015).

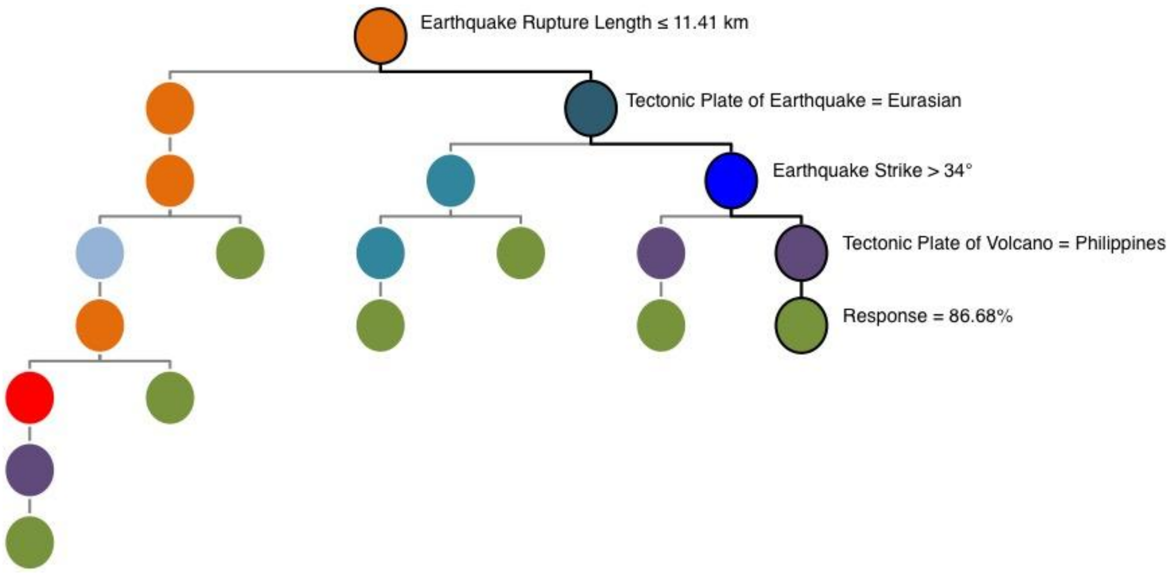


FIGURE 3-8 EXAMPLE OF A FINAL DECISION TREE PRODUCED USING MACHINE LEARNING; IN THIS CASE A RESPONSE WOULD BE EXPECTED FOLLOWING AN EARTHQUAKE IN ASIA IF ALL PARAMETERS ARE MET.

For this research, data based on the parameters identified in Table 3-1 were processed using the approach detailed to identify the conditions that may control any relationship between earthquakes and volcanic activity (Figure 3-10). Firstly, each dataset was split into training (70% of response and non-response case studies identified) and test (30% of response and non-response case studies identified) data. By doing this, the model was able to learn using a subset of data (training data) and then evaluate the model based on unseen data (test data) to compare the predicted results (produced by the model) to recorded earthquake-volcano interactions. Each dataset was then modelled under a bagging approach to obtain the most reliable predictor model. Bagging builds multiple trees over different subsamples of the data and averages their predictions to improve the overall accuracy of the model (Breiman 1996; Dietterich 2002; BigML 2015). In addition ensemble models that process the data over multiple models and synthesise the results were used, rather than a single model, to mitigate the risk of over-fitting and reduce error (Breiman 2001; Dietterich 2002; BigML 2015). For this research, the training data (70% of response and non-response case studies identified) was analysed under a bagging approach that assessed different earthquake-volcano interactions sub-samples over 10 ensemble models.

FIGURE 3-9 EXAMPLE OF A WORKING MODEL (INCLUDING PROCESSING STAGES) DURING MACHINE LEARNING ANALYSES IN BIGML (BIGML 2014).

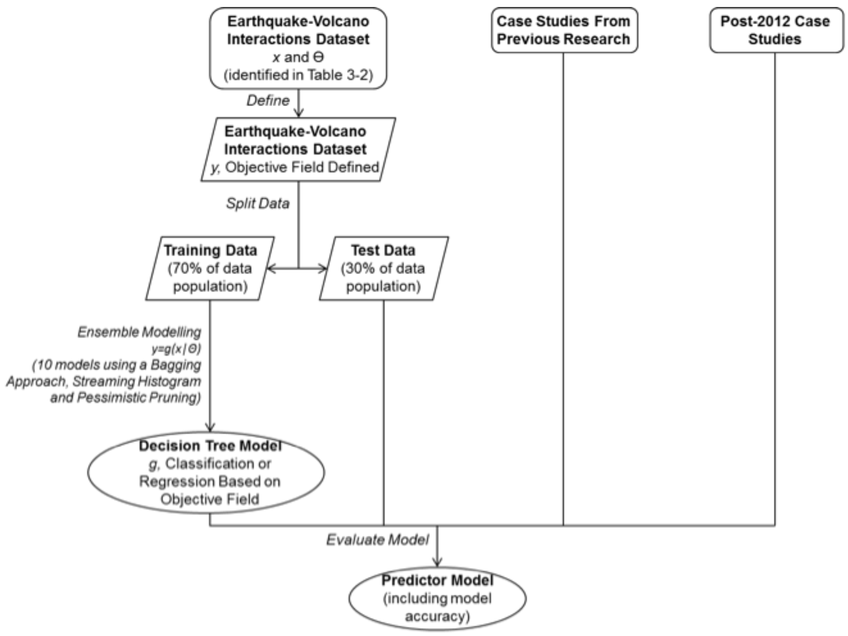


FIGURE 3-10 FLOW DIAGRAM TO SHOW HOW EARTHQUAKE-VOLCANO INTERACTION DATASETS WERE PROCESSED USING MACHINE LEARNING IN BIGML.

In order to ascertain whether the earthquake-volcano event data were statistically different to comparable periods where no response was identified, response and non-response case studies were modelled firstly, Interaction model. To gauge the effect of the relationship within different environments, response case studies were also modelled independently with change in radiant flux, temporal delay and length of response identified as the objective field, *y*. Finally, predictions using case studies from previous research and post-2012 events were performed on the Interaction (response or non-response) model to test the reliability of the results and the predictive utility of the model. In particular, case studies from previous research were used which identified the potentially triggering earthquake and responding volcano as well as their observed interaction. Post-2012 case studies were tested by identifying M≥6.0 earthquakes that occurred between January 2013 and December 2014 to enable change in radiant flux in the following 365 days to be assessed by obtaining the associated MODVOLC data to identify their thermal response.

Following the identification of the conditions that influence triggering, each parameter was analysed in more detail to assess its influence on volcanic response. Overall it was aimed that by identifying the influence of each individual parameter as well as the overall conditions that control a response, the mechanisms suggested in Chapter 2 could be evaluated alongside the key influences encouraging a response. This was performed, initially, by correlating the parameters identified by machine learning to have the largest influence on triggering (referred to herein as ‘controlling’ parameters) to a volcano’s response characteristics, as well as to assess if there are primary and secondary parameters that contribute to the relationship between earthquakes and volcanoes. Individual regions were also assessed to determine the variability in the relationship between different regions and globally, as a whole. Finally, spatial analyses were conducted to determine if there were any distinct spatial differences between response and non-response case studies and examine the influence of spatial parameters on the relationship between earthquakes and volcanoes. The spatial distribution of earthquake-volcano interactions as well as earthquake azimuth and distance to responding volcano and type of earthquake fault were assessed where the earthquake was normalised to 0° latitude, 0° longitude.

3-5 SUMMARY

This chapter has presented methods to identify thermally active volcanoes and their associated volcanic radiant flux as well as outlining three methods that were applied in this research for the identification and examination of earthquake-volcano interactions. While the MIR Brightness-Temperature method, assessments of baselines within volcanic activity and statistical analysis of earthquake-volcano interactions complement each other for the assessment of causative relationships in this thesis, each method can also be applied independently. The development of baselines within satellite-derived volcanic radiant flux data, for example, has a wider application for the assessment of hazards at individual volcanoes, globally and for long-term activity monitoring.

Following the application of these methods to assess any relationship between earthquakes and volcanoes, Objectives 2-5 of this thesis have been addressed. The forthcoming chapters will now present and discuss the results of these methods. Chapter 4 will present the results of the global examination of volcanic radiant flux responses to earthquakes and Chapter 5 will present regional assessments of the parameters that control any interaction between earthquakes and volcanic activity. Within each chapter, the inter-annual variability of volcanic radiant flux, $v + 1\sigma$, developed in Section 3-3 (pg. 67) will be presented in order to identify periods when volcanic flux exceeded the baseline threshold indicating a significant change in activity. The penultimate chapter will then provide an evaluation that each mechanism (identified in Chapter 2) may have on any relationship between earthquakes and volcanic activity.

CHAPTER 4

GLOBAL VOLCANIC RADIANT FLUX RESPONSES TO EARTHQUAKES, 2000-2012

This chapter presents the results of the global assessment of volcanic radiant flux responses to earthquakes. The volcanic radiant flux for each volcano that was identified to be active within the study period will first be detailed as well as presenting the global seismic energy release, 2000-2012. Following this, the temporal coincidence of cumulative volcanic radiant flux and cumulative seismic energy will be analysed. Particular focus will then be placed on examining the global volcanic response to M≥8.0 earthquakes (2001-2011) in order to assess the significance of any association as suggested by previous research. Within this stage, the inter-annual variability in global volcanic flux ($v + 1\sigma$) will also be examined to identify significant changes in volcanic radiant flux following large magnitude events.

4-1 INDIVIDUAL EARTHQUAKE AND VOLCANO TRENDS

During the period 2000-2012, 99 volcanoes were identified by MODVOLC to be thermally active with a total global volcanic radiant flux of 6.92 TW. Figure 4-1a depicts the total energy radiated by each volcano during this period, while Figure 4-1b displays their geographic location. Of the total radiated flux, Kilauea, Hawai'i; Nyiragongo, Democratic Republic of Congo; Etna, Italy; and Nyamuragira, Democratic Republic of Congo account for 57.85% of these emissions radiating at least 3.99 TW of energy. Gaua, Vanautu was the least thermally active volcano, emitting only 57 MW of energy (0.0008% of the total volcanic radiant flux) during the whole period. In terms of their location, 80% of all thermally active volcanoes were located around the Pacific Ring of Fire with additional volcanoes within Africa, Antarctica and Europe experiencing thermal unrest or eruptions.

The cumulative seismic energy released within the same time period is depicted in Figure 4-2. In total, 1.08 x 10^{19} J was released by all M≥4.5 earthquakes between 2000 and 2012. The overall change in seismic energy is generally constant with the most significant changes in seismic energy release being related to large magnitude (M≥8.0) events (further discussed in Section 4-2). In total 14 earthquakes between M8.0 and M9.1 were recorded

FIGURE 4-1 VOLCANOES IDENTIFIED TO BE THERMALLY ACTIVE BY MODVOLC, 2000-2012. A) TOTAL RADIATED ENERGY (MW) BY EACH VOLCANO, B) GEOGRAPHIC LOCATION OF ALL THERMALLY ACTIVE VOLCANOES. APPENDIX II DETAILS THE VOLCANIC RADIANT FLUX AND APPENDIX III PRESENTS THE TEMPORAL DYNAMICS (2000-2012) OF EACH THERMALLY ACTIVE VOLCANO.

between 2001 and 2011 (Table 4-1). Of these events, the largest increase in global seismic energy was related to the 2004 M9.1 Boxing Day earthquake, Sumatra (26/12/2004).

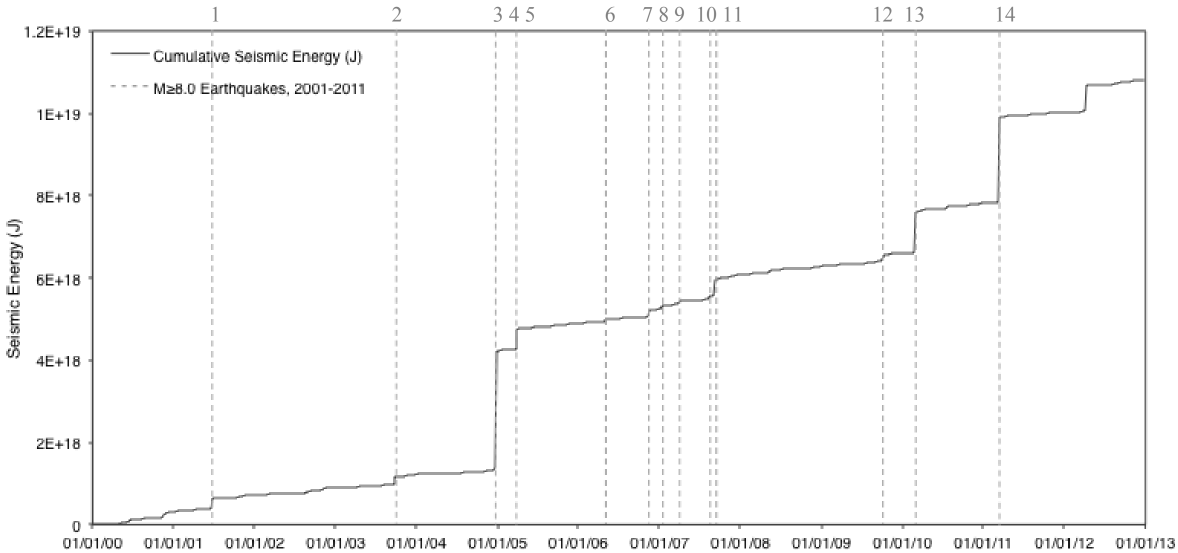


FIGURE 4-2 GLOBAL CUMULATIVE SEISMIC ENERGY (M≥4.5) RELEASED 2000-2012. DOTTED LINES DEPICT ALL M≥8.0 EARTHQUAKES IDENTIFIED IN TABLE 4-1.

TABLE 4-1 SEISMIC ACTIVITY RECORD FOR ALL M≥8.0 EARTHQUAKES, 2001-2011.

Event Number	Date	Time	Magnitude	Latitude (˚)	Longitude (˚)	Depth (km)
1	23/06/2001	20:33:15	8.4	-16.38	-73.50	32.0
2	25/09/2003	19:50:08	8.3	41.86	143.87	27.0
3	23/12/2004	14:59:03	8.1	-49.33	161.42	3.5
4	26/12/2004	00:58:53	9.1	3.29	95.98	30.0
5	28/03/2005	16:09:37	8.6	2.05	97.06	33.7
6	03/05/2006	15:26:40	8.0	-20.15	-174.10	55.0
7	15/11/2006	11:14:13	8.3	46.58	153.27	10.0
8	13/01/2007	04:23:21	8.1	46.23	154.55	10.0
9	01/04/2007	20:39:56	8.1	-8.43	157.06	10.0
10	15/08/2007	23:40:57	8.0	-13.38	-76.61	39.0
11	12/09/2007	11:10:26	8.5	-4.44	101.37	34.0
12	29/09/2009	17:48:10	8.1	-15.48	-172.09	18.0
13	27/02/2010	06:34:11	8.8	-36.12	-72.89	22.9
14	11/03/2011	05:46:24	9.0	38.29	142.37	29.0

4-2 RELATIONSHIP BETWEEN GLOBAL VOLCANIC RADIANT FLUX AND GLOBAL SEISMIC ENERGY

Figure 4-3 displays the temporal coincidence between global volcanic flux and global seismic energy release. Cumulative global volcanic radiant flux has increased steadily during the 12-year period with short phases of rapid increase. Cumulative seismic energy, in comparison, has periods of constant low-level activity followed by large increases in global seismic energy following large magnitude earthquakes. These observed increases relate to each of the M≥8.0 earthquakes identified in Table 4-1. In addition, a further significant increase in seismic energy is observed in April 2012 following two seismic events (M8.6 and M8.2), however due to the 731-day assessment window employed in this thesis (detailed in Chapter 3), this event was not analysed as part of this research. Overall, there is a high temporal correlation (R^2 0.95) between cumulative volcanic radiant flux and cumulative seismic energy with large increases in global volcanic activity (e.g. January 2005) following large magnitude earthquakes (e.g. December 2004).

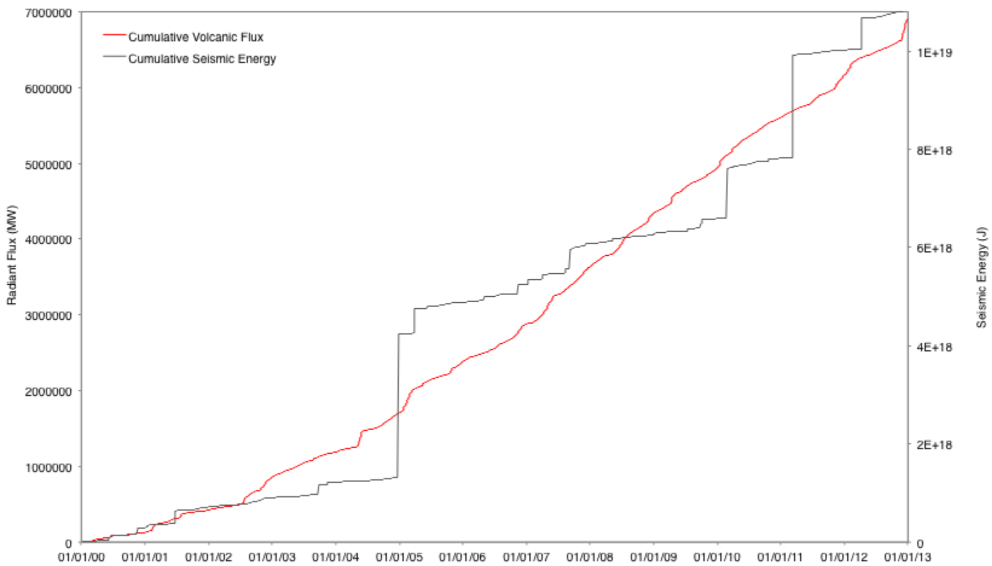


FIGURE 4-3 GLOBAL CUMULATIVE VOLCANIC RADIANT FLUX (RED LINE) AS COMPARED TO GLOBAL CUMULATIVE SEISMIC ENERGY OF ALL M≥4.5 EARTHQUAKES (GREY LINE), 2000-2012.

4-3 GLOBAL RADIANT FLUX RESPONSES TO LARGE MAGNITUDE (M≥8.0) EARTHQUAKES

Increases in global volcanic radiant flux were observed following 8 of the 14 earthquake events, Table 4-2. The remaining 6 instances encountered decreases in volcanic activity by up to 78%. Figure 4-4 depicts the daily global volcanic flux as compared to all M≥8.0 earthquakes between 2001 and 2011 and Figure 4-5 displays the change in flux ±365 days for each M≥8.0 earthquake under study. Within this period, there is a steady level of 'normal' or baseline volcanic radiant flux 2000-2012 with periods of increased activity relating to thermal unrest at individual volcanoes (Figure 4-4). The most significant changes in volcanic activity occurred between December 2004-April 2005 and October 2011-April 2012 (Figure 4-4). In particular, following the 2004 M9.1 Sumatra earthquake, daily volcanic fluxes more than doubled departing from the normal level of daily global flux (Figure 4-5). Between October 2011 and April 2012, global volcanic activity experienced a period of increased flux with both low-level activity at 21 volcanoes and eruptive activity (> 4000 MW) at Nyamuragira, Democratic Republic of Congo (Figure 4-5).

TABLE 4-2 GLOBAL VOLCANIC RADIANT FLUX RESPONSES TO M≥8.0 EARTHQUAKES, 2001-2011*.

Earthquake Date	Earthquake Magnitude	Location	N_b (Total)	N_a (Total)	Change in Number of Erupting Volcanoes [%]	N_a/N_b	β-Statistic	Change in Radiant Flux [%]	Lag [Days]
23/06/2001	8.4	Peru	2.89 (1057)	3.61 (1321)	24.98	1.25	158.11	104.38	44
25/09/2003	8.3	Japan	6.07 (2220)	3.96 (1451)	-34.64	0.65	-343.31	-39.20	216
23/12/2004	8.1	Macquarie Island	4.57 (1672)	6.96 (2549)	52.45	1.52	460.44	141.87	73
26/12/2004	9.1	Sumatra	4.60 (1685)	6.96 (2549)	51.28	1.51	454.00	140.40	75
28/03/2005	8.6	Sumatra	5.70 (2087)	6.61 (2418)	15.86	1.16	137.06	26.86	1
03/05/2006	8.0	Tonga	6.57 (2404)	7.33 (2683)	11.61	1.12	148.97	81.90	81
15/11/2006	8.3	Kuril Islands	6.81 (2491)	7.15 (2617)	5.06	1.05	61.32	78.72	286
13/01/2007	8.1	Kuril Islands	6.72 (2458)	7.16 (2621)	6.63	1.07	75.22	60.65	363
01/04/2007	8.1	Solomon Islands	7.13 (2608)	6.71 (2456)	-5.83	0.94	-64.57	-30.54	2
15/08/2007	8.0	Peru	7.28 (2664)	6.47 (2369)	-11.07	0.89	-119.42	-78.82	3
12/09/2007	8.5	Sumatra	7.27 (2662)	6.44 (2358)	-11.42	0.89	-123.86	-55.66	12
29/09/2009	8.1	Samoa Islands	7.97 (2918)	6.83 (2499)	-14.36	0.86	-192.85	-20.18	16
27/02/2010	8.8	Chile	7.61 (2784)	6.19 (2265)	-18.64	0.81	-264.24	-45.37	4
11/03/2011	9.0	Japan	6.15 (2251)	6.65 (2435)	8.17	1.08	92.87	25.34	339

* - *N_b (Total)* and *N_a (Total)* reports the average (and total) number of erupting volcanoes 365 days *preceding* and *following* an earthquake, respectively. *Change in the Number of Erupting Volcanoes [%]* and *N_a/ N_b* indicate the change in the daily number of erupting volcanoes. *β-statistic* indicates the significance of any association between earthquakes and the number of erupting volcanoes. *Change in Radiant Flux [%]* indicates the largest daily percentage change in summed volcanic radiant flux up to 365 days following the earthquake as compared to the same number of days preceding the earthquake up to 365 days and, finally, *Lag [Days]* reports the number of days for the largest percentage change in radiant flux up to 365 days following the earthquake to occur.

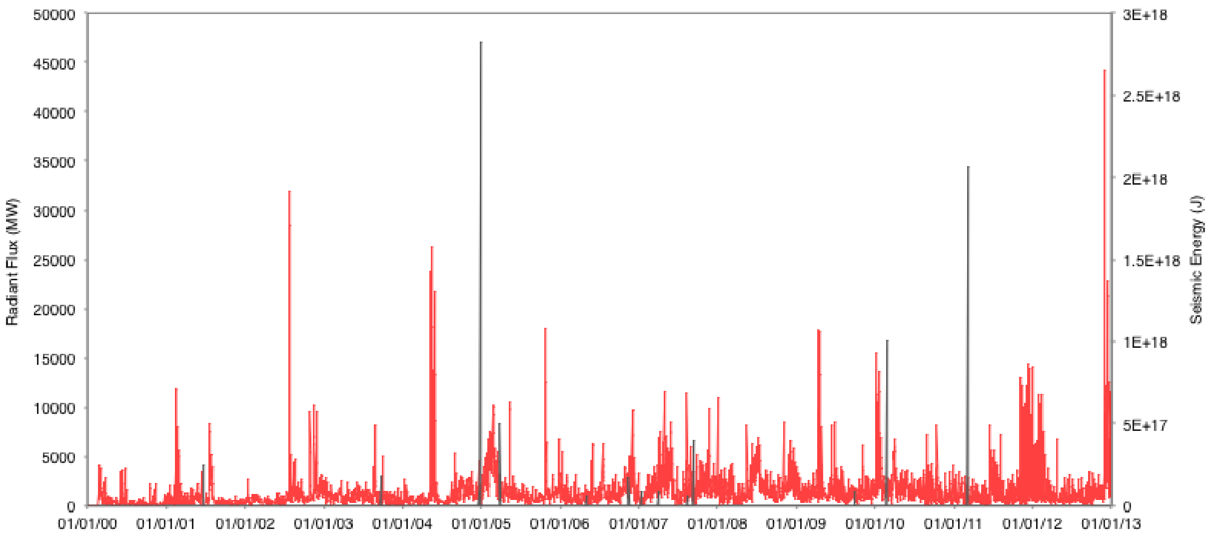


FIGURE 4-4 DAILY GLOBAL VOLCANIC RADIANT FLUX (RED LINE) 2000-2012 COMPARED TO THE SEISMIC ENERGY OF ALL M≥8.0 EARTHQUAKES (GREY LINES) 2001-2011.

Of the 14 potential earthquake-volcano interactions analysed, 4 experienced significant changes in activity following an earthquake based on their associated β-statistic (which reports the significance of the change in the number of erupting volcanoes N_b and N_a in standard deviations) and change in volcanic flux (where the probability density function classifies the significance of the change in volcanic radiant flux as compared to change in volcanic radiant flux following each M≥8.0 earthquake) (Table 4-2; Figure 4-6). The two most significant increases in global volcanic activity followed the M9.1 Sumatra earthquake (26/12/2004) and the M8.4 Peru earthquake (23/06/2001), while the two most significant decreases in global volcanic flux followed the M8.8 Chile earthquake (27/02/2010) and the M8.3 Japan earthquake (25/09/2003). Although the largest increase in volcanic radiant flux followed a M8.1 earthquake (23/12/2004), its occurrence just 3 days before the largest earthquake in the 21st Century, means that this temporally coincident event is analysed rather than the M8.1 earthquake. Figure 4-7 depicts the daily global volcanic radiant flux as compared to $v + 1\sigma$ (inter-annual variability in volcanic flux) over the 731-day assessment window for these 4 events as defined in Section 3-3 (pg. 67). In addition, in Figure 4-7, the insets display the probability density function that was used to identify the significance of change in volcanic radiant flux as compared to change in volcanic radiant flux following each M≥8.0 earthquake. Figure 4-8 then compares the daily number of erupting volcanoes, N_b and N_a, based on the 731-day assessment window as well as the overall β-statistic for each of these events. The daily number of erupting volcanoes was obtained by summing the number of thermally active volcanoes on a given day and the associated N_b and N_a averages were derived from the total number of thermally active volcanoes 365 days before and after an earthquake.

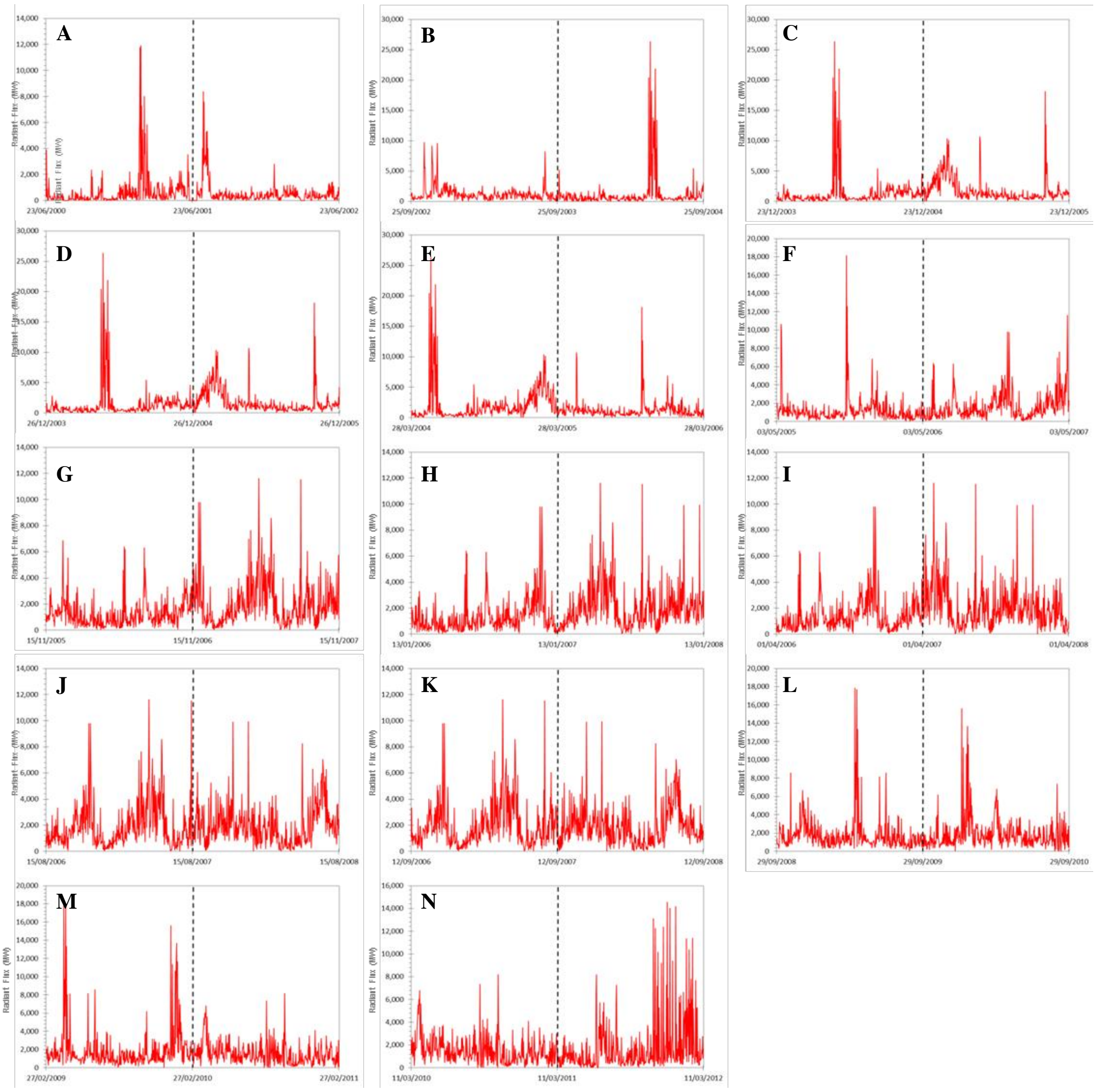


FIGURE 4-5 DAILY GLOBAL VOLCANIC RADIANT FLUX ±365 DAYS FOR EACH M≥8.0 EARTHQUAKE IDENTIFIED IN TABLE 4-1. A) M8.4, 23/06/2001, B) M8.3, 25/09/2003, C) M8.1, 23/12/2004, D) M9.1, 26/12/2004, E) M8.6, 28/03/2005, F) M8.0, 03/05/2006, G) M8.3, 15/11/2006, H) M8.1, 13/01/2007, I) M8.1, 01/04/2007, J) M8.0, 15/08/2007, K) M8.5, 12/09/2007, L) M8.1, 29/09/2009, M) M8.8, 27/02/2010, N) M9.0, 11/03/2011. DASHED LINE REPRESENTS THE EARTHQUAKE.

Examinations of global volcanic activity following the remaining M≥8.0 earthquakes did not identify significant changes in volcanic radiant flux on the basis of the β-statistic and percentage change in volcanic flux (Table 4-2; Figure 4-6). Of the 10 events, 60% [6] experienced periods of increased volcanic radiant flux following an earthquake and 40%

[4] experienced periods of decreased activity. For periods of increased activity, the average number of erupting volcanoes (N_a-N_b) increased by at least one. In contrast, in the year following an earthquake, the largest decrease in the number of erupting volcanoes was -14.36% (from N_b 7.97 to N_a 6.83). In the majority of cases (70%), change in volcanic radiant flux occurred within 90 days of a M≥8.0 earthquake with the longest change in global volcanic radiant flux occurring after 363 days. The smallest increase (25.34%) in volcanic flux followed the M9.0 Japan earthquake (11/03/2011) occurring over 339 days while the largest decrease in volcanic radiant flux followed a M8.0 earthquake (-78.82%, 15/08/07). When compared to other earthquake events, however, the corresponding β-statistic (92.87 and -119.42, respectively) shows that changes in volcanic activity following these events were not significant. Further β-statistics indicate low-level changes in the number of erupting volcanoes following an earthquake, however, changes in volcanic radiant flux of more than ±100% following these events were not observed.

While each of these periods of change in volcanic activity may be the result of triggering, on the basis of the response criteria identified in Chapter 3 they are not identified as triggered in this thesis. Chao *et al*. (2013) and Takada and Fukushima (2013), for example, identified triggered seismicity and volcanic deformation following the 2011 M9.0 Japan earthquake. Yet on the basis of change in volcanic radiant flux, 25.34%, and the β-statistic, 92.87, this thesis does not identify significant changes in thermal volcanic activity (Table 4-2; Figure 4-6). Further to this, the varying levels of response observed following each M≥8.0 earthquake (Table 4-2; Figure 4-5) demonstrates that not all earthquakes result in volcanic activity triggering. Thus, the lack of a defined pattern of response following M≥8.0 earthquakes provides evidence to support the theory that a number of conditions exist which determine a volcano's response. It is possible, therefore, that the changes induced by an earthquake (e.g. changes in the stress field) may initiate different processes of unrest and different types of response may be observed. For example, following the 2011 M9.0 Japan earthquake only instances of increased seismicity and volcanic deformation were observed whereas the 2004 M9.1 event initiated changes in global thermal activity. This may be due to differences in each earthquake's characteristics (e.g. earthquake magnitude and location) or an individual volcano's threshold or readiness for response (i.e. critical state) (Hill *et al*. 2002; West *et al*. 2005; Eggert and Walter 2009). A more detailed assessment of these conditions will be conducted Chapter 5: Regional Relationships Between Earthquakes and Volcanic Activity.

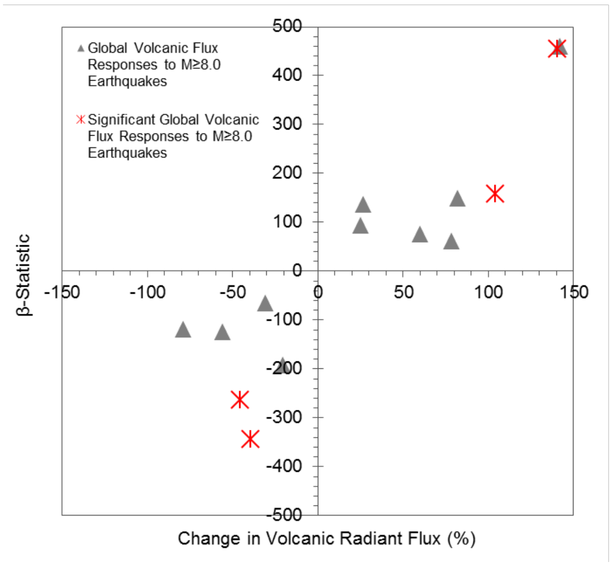


FIGURE 4-6 CHANGE IN VOLCANIC RADIANT FLUX (%) AS COMPARED TO THE β-STATISTIC FOR ALL M≥8.0 EARTHQUAKES, 2001-2011. RED CROSSES INDICATE SIGNIFICANT CHANGES IN VOLCANIC ACTIVITY FOLLOWING AN EARTHQUAKE.

4-3-1 M9.1 SUMATRA (26/12/2004)

Following the 2004 M9.1 Sumatra earthquake, global volcanic flux increased by 140.40% (Table 4-2). Within the 3 months following the earthquake, daily volcanic radiant flux increased exceeding $v + 1\sigma$ (the inter-annual variability in volcanic radiant flux, Figure 4-7a) and resulting in a summed emission of 196,265 MW (3% of the total radiated energy, 2000-2012). Following this, daily global volcanic radiant flux decreased and remained below $v + 1\sigma$ for the majority of the period. Figure 4-8a shows that the average number of erupting volcanoes also increased from N_b 4.60 to N_a 6.96 (51.28%) with new eruptions at 10 volcanoes including Barren Island, Indonesia; Fernandina, Ecuador; Karthala, Comoros and Sierra Negra, Galapagos Islands that were particularly noteworthy due to their long repose periods (previous eruptive activity in 1994, 1995, 1991 and 1980, respectively).

On the basis of the β-statistic 454.00 and change in volcanic flux (%) 0.00013 <0.005 (Figure 4-6), this increase in global volcanic activity is identified to be significant and it can be suggested that the 2004 M9.1 earthquake triggered this response. Importantly, this contrasts with the findings of Harris and Ripepe (2007) who stated that there were no triggered responses following the 2004 event and supports previous research by demonstrating that earthquakes can influence volcanic activity at a global scale (Linde and Sacks 1998; West *et al*. 2005; Lemarchand and Grasso 2007). Furthermore, this research contrasts with Delle Donne *et al*. (2010) who reported a 300% increase in global volcanic flux following this event as compared to the 140.40% change reported in this research.

The occurrence of a M8.1 earthquake (Macquarie Islands, 23/12/2004) just 3 days before the largest earthquake in the 21st Century means that this temporally coincident event could also have been the cause of enhanced volcanic activity. The onset of an 11-minute earthquake swarm at Mount Wrangell, Alaska, following the passage of seismic waves 1-hour after the initial M9.1 earthquake, however, provides evidence to attribute these responses to this event (West *et al*. 2005). In fact, West *et al*. (2005) stated that the earlier M8.1 earthquake, which produced stresses one order of magnitude smaller than the M9.1 event (8.91×10^{23} J as compared to 2.82×10^{25} J, respectively), did not trigger similar anomalous activity. Alongside this, Manga and Brodsky (2006) suggested that a later M8.6 earthquake, Sumatra (28/03/2005) was the trigger for new activity at Barren Island, Indonesia. Statistical assessments of change in volcanic radiant flux, 28.85%, and the β-statistic, 137.06 (calculated in this thesis), however, identified that changes following the March 2005 M8.6 event, Sumatra were much smaller (Table 4-2). This evidence corresponds with Walter and Amelung (2007) who attributed the eruption at Barren Island, Indonesia to a transfer of stress south of the earthquake's epicentre that initiated a sequence of events including the M9.1 and M8.6 earthquakes.

4-3-2 M8.8 CHILE (27/02/2010)

Within 1 month of the 2010 M8.8 Chile earthquake, daily volcanic radiant flux emissions had increased to over 4,000 MW per day (Figure 4-7b). Despite this initial increase, however, Figure 4-7b shows that during the remainder of the year following this event global volcanic radiant flux remained below $v + 1\sigma$ resulting in an overall decrease of 45.37%. Corresponding with these results, Figure 4-8b shows that the number of volcanoes experiencing thermal unrest, N_b 7.61 as compared to N_a 6.19, also decreased (-18.64% with thermal activity ceasing at 14 volcanoes) reaching the lowest number of volcanoes experiencing thermal unrest 6 months after the event (N_a 1.00). When compared to all other M≥8.0 earthquakes, this decrease in global volcanic activity is identified to be significant as based on the β-statistic (-264.24) and probability density function (0.0036 *>0.005*) therefore confirming the ability of large magnitude earthquakes to inhibit as well as enhance global volcanic activity following an event.

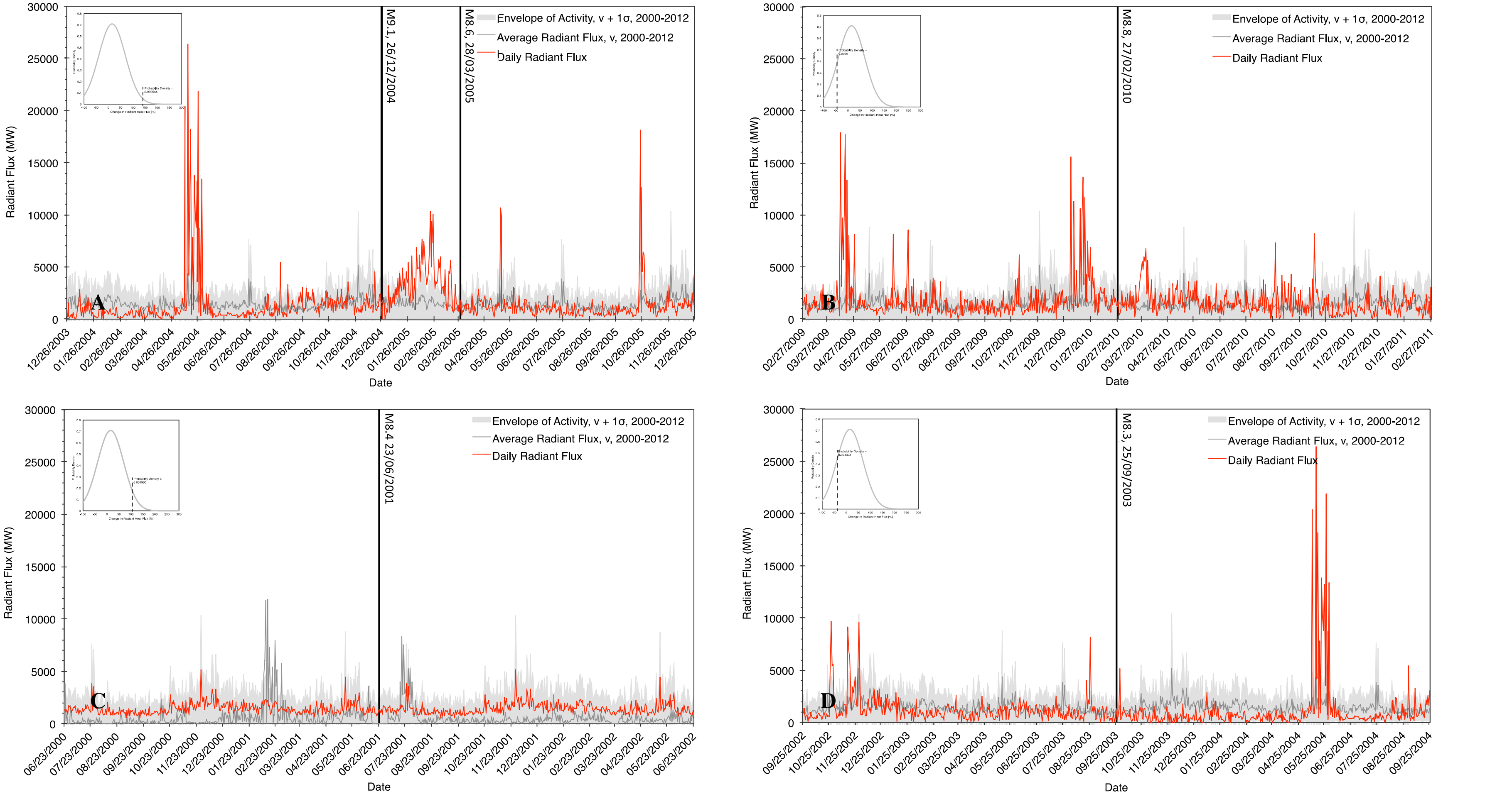


FIGURE 4-7 DAILY VOLCANIC RADIANT FLUX (RED LINE) ±365 DAYS RELATIVE TO A) M9.1, 26/12/2004; B) M8.8, 27/02/2010; C) M8.4 23/06/2001 AND D) 25/09/2003 EARTHQUAKES AS COMPARED TO *V* (AVERAGE RADIANT FLUX, DARK GREY LINE) AND *V* + 1σ (LIGHT GREY ENVELOPE). INSETS DISPLAY THE PROBABILITY DENSITY FUNCTION WHICH CLASSIFIES THE SIGNIFICANCE OF THE CHANGE IN VOLCANIC RADIANT FLUX AS COMPARED TO CHANGE IN VOLCANIC RADIANT FLUX FOLLOWING EACH M≥8.0 EARTHQUAKE.

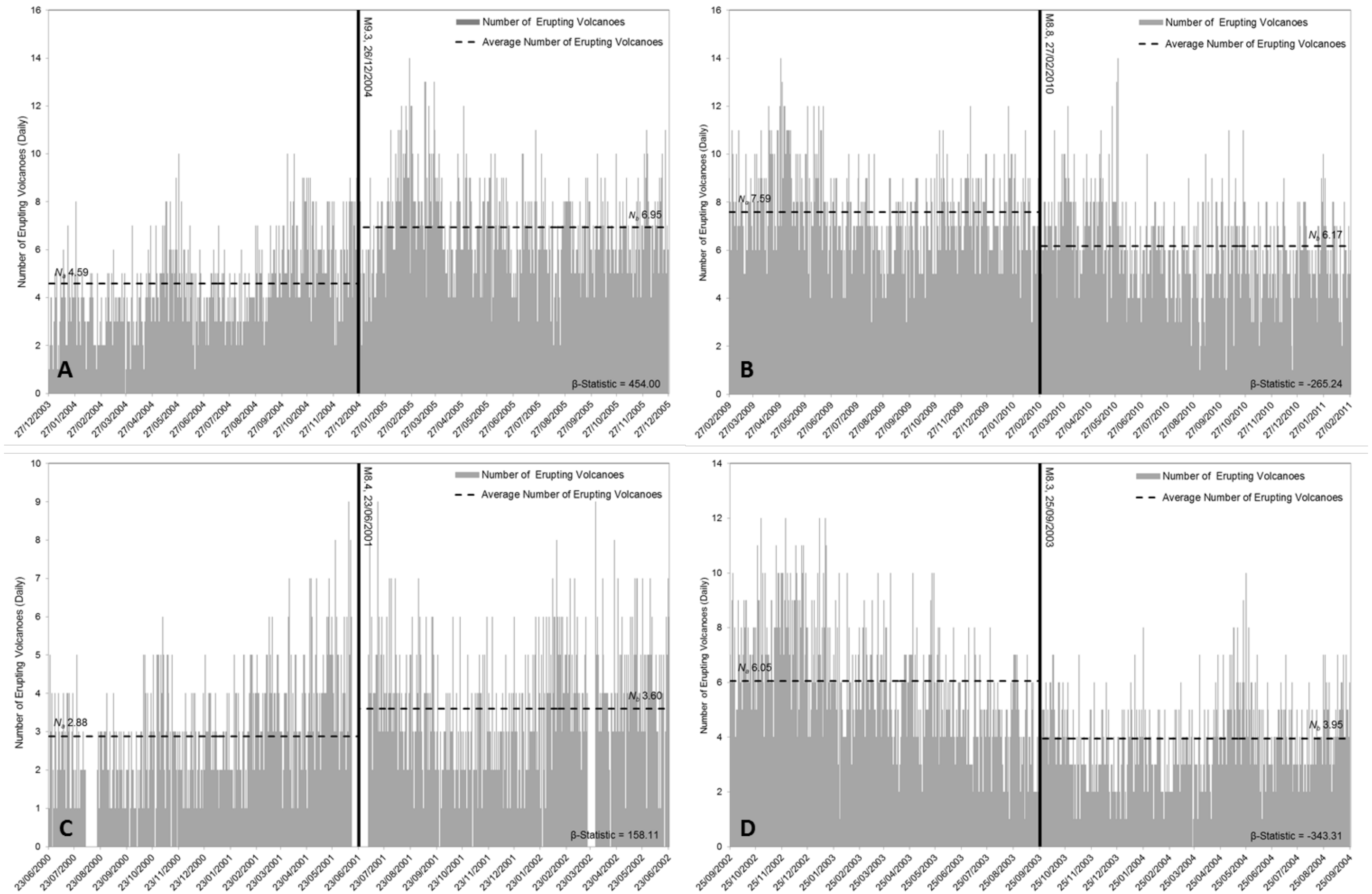


FIGURE 4-8 HISTOGRAM SHOWING THE DAILY NUMBER OF ERUPTING VOLCANOES ±365 DAYS RELATIVE TO A) M9.1, 26/12/2004; B) M8.8, 27/02/2010; C) M8.4 23/06/2001 AND D) 25/09/2003 EARTHQUAKES. BLACK DASHED LINE REPRESENTS N_b AND N_a AND BLACK LINE INDICATES THE EARTHQUAKE EVENT.

In contrast to the findings of this thesis, however, deformation assessments identified volcanic subsidence of up to 15 cm around volcanic centres in the Andean Southern Volcanic Zone following the 2010 M8.8 event (Lupi *et al*. 2012; Mora-Stock *et al*. 2012; Pritchard *et al*. 2013). While different periods of unrest following earthquake triggering have been noted previously (e.g. Hill *et al*. 1995; Hill *et al*. 2002; Manga and Brodsky 2006), instances of decreased thermal activity alongside volcanic subsidence have not been reported. This suggests that changes following an earthquake can initiate different processes of unrest, which will result in different periods of response being observed. As suggested by Walter and Amelung (2007) decreases in volcanic activity may be located in areas of decreased strain where an eruption is discouraged. Instances of decreased thermal activity and volcanic subsidence as observed following this event may, therefore, reflect the pattern of stress change following this event. In particular, the earthquake may have resulted in a decrease in stress over the South American plate but an increase in stress on the Nazca plate where, with the exception of volcanoes on the Galapagos Islands, there are no volcanoes that could be triggered.

4-3-3 M8.4 PERU (23/06/2001)

Responses following the 2001 M8.4 Peru earthquake (23/06/2001) also identified an important characteristic that has not been previously identified. Figure 4-7c displays the global daily volcanic radiant flux as compared to $v + 1\sigma$ and shows that in the year following the earthquake, the rate of thermal flux remained constant in line with pre-earthquake emission levels for the majority of the period. In fact, despite a small increase overall (104.38%), the average daily volcanic flux decreased from 633 MW before the earthquake to 528 MW after the event. In contrast, the average number of volcanoes experiencing thermal unrest changed significantly (β-statistic 158.11) increasing from N_b 2.89 to N_a 3.61 (24.98%, Figure 4-8c). Critically, this demonstrates that, in addition to volcanic radiant flux, the number of volcanoes experiencing thermal unrest following an earthquake appears to be an important indicator of triggering at a global scale. For example, while an earthquake may not trigger explosive volcanic eruptions a seismic event may initiate low-level thermal activity at a number of volcanoes which also signifies an increased response of volcanoes to earthquakes.

4-2-4 M8.3 JAPAN (25/09/2003)

In the period preceding the 2003 M8.3 Japan earthquake, global volcanic activity exhibited 452,704 MW of energy. Following this event, however, daily global volcanic flux remained within $v + 1\sigma$ and, with exception of an eruption at Nyamuragira, Democratic Republic of Congo, fell below the average volcanic radiant flux, v, for the year following the earthquake (-39.20%, Figure 4-7d). This event also observed the most significant decrease in the number of erupting volcanoes from N_b 6.07 to N_a 3.96 (-34.64%, Figure 4-8d) on the basis of the β-statistic (343.31) with activity ceasing at 13 volcanoes.

While decreases in volcanic activity may indicate a reduction in the current risk posed to society, the conditions that lead to decreases in thermal unrest, like deformation changes, are critical in determining the parameters that influence a volcano's response as well as how different volcanoes may respond to an earthquake trigger. Conversely, it may be possible that an earthquake triggers decreases in volcanic activity immediately after an earthquake followed by an increase in volcanic activity at a later period. For example, Wooster and Rothery (1997) identified decreases in thermal activity prior to major eruptions at Lascar, Chile. Therefore, by determining the factors that inhibit volcanic activity following an earthquake as compared to the conditions that result in increased activity or instances of no triggering, it may be possible to understand the relationship between earthquakes and volcanic activity for volcanic activity forecasting.

4-3 SUMMARY

This chapter has presented and discussed the results of global volcanic radiant flux responses to large magnitude earthquakes. Both increased and decreased activity were observed with the typical response involving a short period of increased or decreased volcanic flux followed by a return to pre-earthquake emissions. The differing global volcanic flux responses observed following each M≥8.0 earthquake provides evidence to suggest that different processes act following an earthquake, as demonstrated. The following chapter will now present the results of the regional assessment of changes in volcanic activity following a seismic event. Chapter 6 will then discuss the results of these assessments in relation to the processes that influence any relationship between earthquakes and volcanoes as well as evaluating the mechanisms that may control triggering.

CHAPTER 5

REGIONAL RELATIONSHIPS BETWEEN EARTHQUAKES AND VOLCANIC ACTIVITY

The previous chapter presented and discussed the results of the global assessment of volcanic radiant flux responses to seismic events. This chapter will now detail interactions between earthquakes and volcanoes within a regional setting (< 1,000 km). All cases of potentially triggered earthquake-volcano interactions will first be identified. Within this stage, examples of the inter-annual variability in volcanic radiant flux, $v + 1\sigma$, will be provided to demonstrate the criteria that had to be met for a volcano to be classed as potentially triggered. Instances of non-response and decreases in activity will also be presented to enable a comparison of the conditions that may influence volcanic activity following earthquakes to be conducted. Based on these case studies, the parameters associated with each individual earthquake-volcano interaction will then be detailed and examined. A volcano's typical response following an earthquake trigger will also be presented and the significance of this change assessed. Here an examination of the parameters identified to control any relationship will be presented. Case studies from previous research and post-2012 activity will also be analysed to identify the predictive utility of the earthquakes as a precursor to volcanic activity. Finally, statistical and spatial analyses will be presented in order to show any variability in the relationship as well as the role of primary and secondary controlling parameters.

5-1 INTERACTIONS BETWEEN REGIONAL EARTHQUAKES AND VOLCANIC ACTIVITY

In total, 85 instances of thermal unrest were identified following earthquakes in the period 2000-2012, Table 5-1 and Figure 5-1. Of the 99 volcanoes identified to be active by MODVOLC, 52 experienced responses to an earthquake trigger with 21 volcanoes showing evidence of multiple instances of triggering. The remaining 47 volcanoes experienced periods of thermal unrest, however, they did not meet the criteria (detailed in Section 3-4-2-1, pg. 74) to be classed as responding for this research. Importantly, these responses demonstrate that interactions between earthquakes and volcanoes are not universal, therefore supporting previous research that suggested that a number of conditions must be met for a response to occur (Hill *et al*. 2002; Walter *et al*. 2009; Bebbington and Marzocchi 2011).

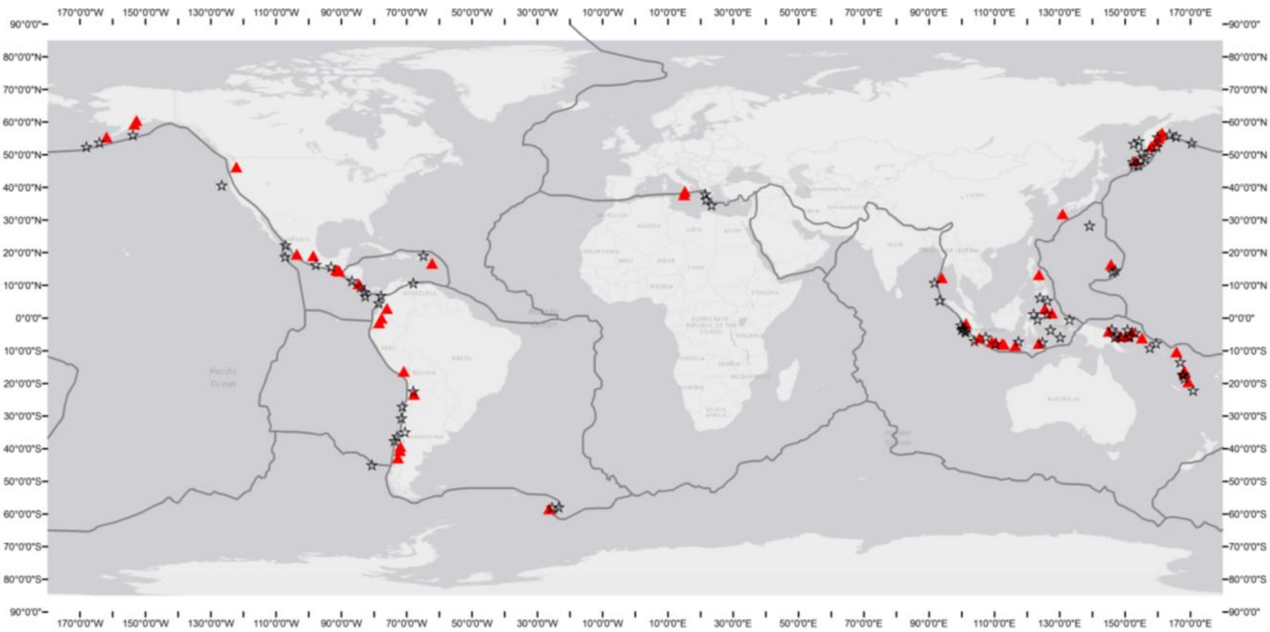


FIGURE 5-1 SPATIAL DISTRIBUTION OF EARTHQUAKE-VOLCANO INTERACTIONS, 2000-2012. OVERALL, 71% OF TRIGGERED VOLCANOES WERE LOCATED ON THE SAME TECTONIC PLATE AS THE TRIGGERING EARTHQUAKE. RED TRIANGLES REPRESENT RESPONDING VOLCANOES AND STARS REPRESENT TRIGGERING EARTHQUAKES.

In terms of the triggering earthquake, 4.77% [82] of all M≥6.0 earthquakes [1,720] recorded by the USGS NEIC (2001-2011) resulted in a volcanic response. In addition, 3 seismic events were identified to initiate thermal unrest at more than one volcano (Table 5-1). Further examination of each instance of multiple volcanic responses identified that all volcanoes were located in a similar incoming earthquake wave direction and azimuth (e.g. Figure 5-2). In contrast, volcanoes within the same geographic region but located in an opposite plane did not respond (e.g. Figure 5-2). On the basis of these triggered and non-triggered responses located in different planes it is evident that the characteristics of the triggering earthquake plays a key role in initiating a response. The mechanism of rupture directivity, in which seismic waves resulting from an earthquake are stronger along a certain path, supports the triggering of volcanoes depending on the direction of seismic wave propagation (i.e. earthquake fault characteristics) (Delle Donne *et al*. 2010). These findings support the theory of Sánchez and McNutt (2004) who surmised that volcanoes aligned with azimuth of fault rupture are likely to be triggered.

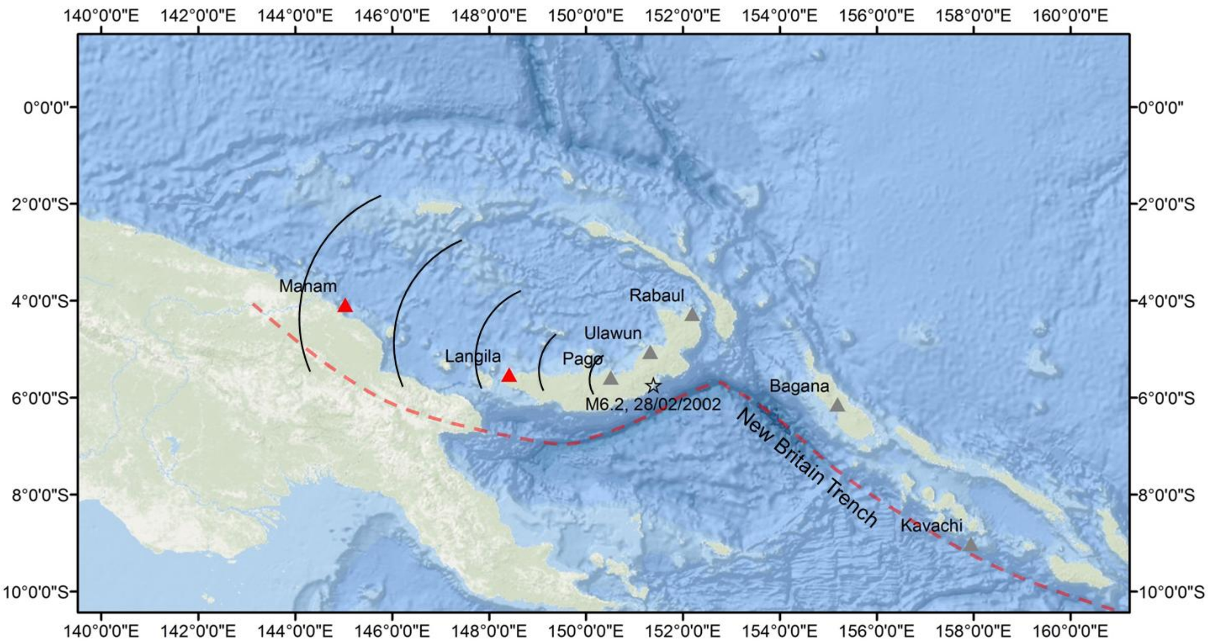


FIGURE 5-2 RESPONDING (RED TRIANGLES) AND NON-RESPONDING (GREY TRIANGLES) VOLCANOES FOLLOWING A M6.2 EARTHQUAKE (STAR), INDONESIA. RED DASHED LINE REPRESENTS THE NEW BRITAIN TRENCH AND BLACK LINES REPRESENT THE LIKELY PROPAGATION OF SEISMIC WAVES.

Table 5-1 presents the percentage change in volcanic radiant flux and the corresponding β-statistic that were employed as response criteria for each earthquake-volcano interaction, alongside details of the triggering earthquake and responding volcano. Examples of the inter-annual variability in volcanic radiant flux, $v + 1\sigma$, are demonstrated in Figure 5-3. Figure 5-3a demonstrates the identification of a period of increased volcanic flux following an earthquake at Kliuchevskoi, Russia a volcano that had on-going activity within the study period. Figure 5-3b presents an example at Mayon, Philippines a volcano with intermittent periods of unrest where $v + 1\sigma$ is exceeded indicating a significant change in baseline volcanic activity. Additional graphs presenting the daily volcanic flux as compared to $v + 1\sigma$ for each volcano that experienced triggering are provided in Appendix III.

This research also identified 2 instances of decreased volcanic activity at Etna, Italy and Colima, Mexico (Table 5-2). In both cases decreases in activity did not reach the ±100% criteria identified in Chapter 3. Figure 5-4 demonstrates the absence of volcanic radiant flux detections within 12 and 3 days of the triggering earthquake, respectively. Due to the small number of cases of decreased volcanic activity identified, further analyses of earthquake and volcano parameters were not conducted as they would not reliably determine the parameters that influence decreases in volcanic activity. Despite this, these instances of decreased volcanic activity following an earthquake, like global instances of decreased activity, are extremely important, confirming the ability of earthquakes to both enhance volcanic thermal activity as well as inhibit activity as observed following the 2002 Denali Fault earthquake, Alaska [03/11/2002] (Sánchez and McNutt 2004). In addition, the differences in the parameters influencing decreases in activity as compared to increased volcanic activity following an earthquake may provide valuable insights into the conditions that influence the type of response observed.

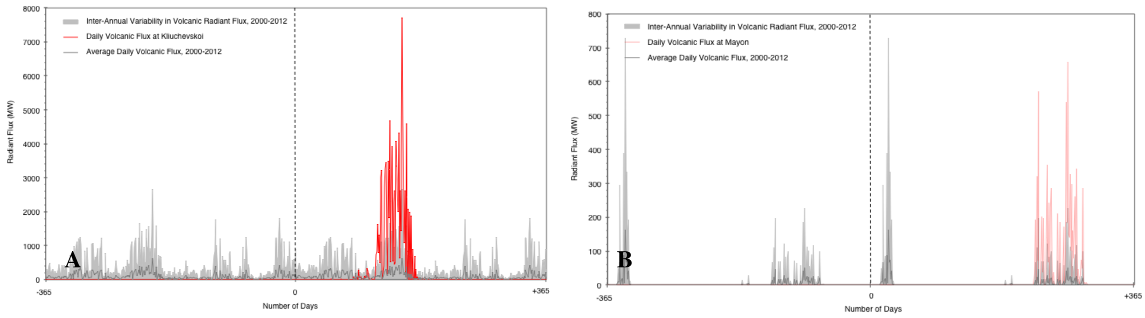


FIGURE 5-3 EXAMPLES WHERE $v + 1\sigma$ (INTER-ANNUAL VARIABILITY IN VOLCANIC RADIANT FLUX) IS EXCEEDED IDENTIFYING POTENTIALLY TRIGGERED INTERACTIONS FOR ON-GOING ACTIVITY AT KLIUCHEVSKOI, RUSSIA (A) AND INTERMITTENT PERIODS OF UNREST AT MAYON, PHILIPPINES (B), DASHED LINE REPRESENTS THE TRIGGERING EARTHQUAKE. FURTHER EXAMPLES OF $v + 1\sigma$ AS COMPARED TO DAILY VOLCANIC FLUX ARE PRESENTED IN APPENDIX III.

Considering the aims of this thesis to identify the parameters that influence volcanic activity triggering following an earthquake, this thesis identified instances where changes in volcanic thermal activity following an earthquake did not meet the criteria to be classed as triggered in this research. Table 5-3 identifies the percentage change in volcanic radiant flux and β-statistic as well as details of the earthquake and volcano for these cases of non-triggered activity and Figure 5-5 presents examples where $v + 1\sigma$ were not exceeded. By identifying the earthquake and volcano parameters associated with these cases of non-triggered earthquake-volcano interactions comparisons to the parameters of triggered earthquake-volcano interactions can be made to identify the earthquake and volcanic characteristics that influence volcanic activity triggering following earthquakes. These instances have a particular utility in this thesis to enable differences in the characteristics of triggered and non-triggered activity to be determined and, following future seismic events, identify whether a response would be expected.

TABLE 5-1 INSTANCES OF EARTHQUAKE-VOLCANO INTERACTIONS AS IDENTIFIED USING RESPONSE CRITERIA IDENTIFIED IN CHAPTER 3 (ORDERED BY DATE OF THE TRIGGERING EARTHQUAKE).

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Date of Volcanic Response	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
1R	16/02/2001	6.0	-7.15	117.42	Merapi	23/02/2001	-7.54	110.44	3423.01	775.30
2R	02/08/2001	6.3	56.22	163.70	Shiveluch	02/08/2001	56.65	161.36	372.32	412.50
3R	30/09/2001	6.2	-18.46	168.26	Ambrym	02/10/2001	-16.25	168.12	680.01	161.18
4R	13/11/2001	6.0	22.30	-107.03	Colima	16/02/2002	19.51	-103.62	Inf	Inf
5R	13/11/2001	6.0	53.61	170.44	Karymsky	19/01/2002	54.05	159.45	Inf	Inf
6R	28/11/2001	6.4	15.68	-93.11	Fuego	05/01/2002	14.47	-90.88	29618.97	1607.01
7R	15/01/2002	6.0	-17.42	167.90	Yasur	31/01/2002	-19.53	169.44	3125.47	499.47
8R	28/02/2002	6.2	-5.74	151.40	Langila	25/05/2002	-5.53	148.42	Inf	Inf
9R	28/02/2002	6.2	-5.74	151.40	Manam	07/04/2002	-4.08	145.04	Inf	Inf
10R	27/06/2002	6.5	-6.97	103.96	Semeru	27/06/2002	-8.11	112.92	739.86	387.59
11R	03/07/2002	6.1	-5.06	147.52	Pago	06/08/2002	-5.58	150.52	Inf	Inf
12R	30/07/2002	6.1	-57.88	-23.34	Mount Belinda	30/07/2002	-58.42	-26.33	215.25	189.34
13R	31/07/2002	6.5	7.93	-82.78	Arenal	11/09/2002	10.46	-84.70	569.46	155.06
14R	14/08/2002	6.5	14.08	146.32	Anatahan	10/05/2003	16.35	145.67	Inf	Inf
15R	16/06/2003	6.8	55.46	159.93	Kliuchevskoi	19/07/2003	56.06	160.64	1371.99	490.06
16R	20/06/2003	6.8	-30.65	-71.53	Villarrica	10/07/2003	-39.42	-71.93	2875.49	478.28
17R	05/12/2003	6.6	55.57	165.73	Shiveluch	11/01/2004	56.65	161.36	152.81	148.98
18R	17/03/2004	6.0	34.58	23.41	Etna	10/09/2004	37.73	15.00	Inf	Inf
19R	13/05/2004	6.3	-3.60	150.78	Manam	21/10/2004	-4.08	145.04	Inf	Inf
20R	28/07/2004	6.5	-0.50	133.08	Ibu	24/08/2004	1.49	127.63	Inf	Inf
21R	28/07/2004	6.5	-0.50	133.08	Karangetang	16/10/2004	2.78	125.40	1254.21	163.77
22R	28/08/2004	6.5	-34.92	-70.46	Villarrica	05/11/2004	-39.42	-71.93	348.5	158.17
23R	11/09/2004	6.1	-58.01	-25.41	Mount Belinda	17/09/2004	-58.42	-26.33	220.04	198.06
24R	04/10/2004	6.0	14.60	147.09	Anatahan	06/01/2005	16.35	145.67	550.11	147.05

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Date of Volcanic Response	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
25R	09/10/2004	6.9	11.40	-86.70	Fuego	12/10/2004	14.47	-90.88	202.53	417.78
26R	16/11/2004	6.1	-5.61	151.51	Langila	24/11/2004	-5.53	148.42	1165.95	278.55
27R	20/11/2004	6.4	9.58	-84.13	Pacaya	24/12/2004	14.38	-90.60	Inf	Inf
28R	18/12/2004	6.2	48.83	156.28	Kliuchevskoi	16/01/2005	56.06	160.64	8570.70	336.92
29R	22/01/2005	6.3	-7.75	159.58	Rabaul	31/01/2005	-4.27	152.20	19885.25	1396.57
30R	07/02/2005	6.1	-4.52	153.24	Bagana	11/02/2005	-6.14	155.20	149.50	102.16
31R	11/04/2005	6.6	-3.46	145.99	Langila	19/04/2005	-5.53	148.42	206.91	136.59
32R	18/05/2005	6.1	5.44	93.36	Barren Island	26/05/2005	12.28	93.86	Inf	Inf
33R	17/06/2005	6.6	40.67	-126.61	Mount St Helens	26/06/2005	46.20	-122.18	306.78	167.47
34R	25/09/2005	6.1	-17.49	167.86	Lopevi	27/10/2005	-16.51	168.35	10693.66	495.45
35R	15/10/2005	6.1	46.83	154.13	Karymsky	23/11/2005	54.05	159.45	304.34	306.29
36R	17/11/2005	6.8	-22.40	-67.92	Ubinas	23/05/2006	-16.36	-70.90	Inf	Inf
37R	20/11/2005	6.2	53.83	-164.02	Augustine	17/01/2006	59.36	-153.43	Inf	Inf
38R	30/11/2005	6.4	6.25	124.01	Mayon	15/07/2006	13.26	123.69	Inf	Inf
39R	23/01/2006	6.4	-17.36	167.78	Tinakula	11/02/2006	-10.38	165.80	Inf	Inf
40R	23/01/2006	6.2	6.88	-77.77	Tungurahua	08/04/2006	-1.47	-78.44	Inf	Inf
41R	30/04/2006	6.6	-27.07	-71.22	Lascar	12/06/2006	-23.37	-67.73	Inf	Inf
42R	26/05/2006	6.3	-7.96	110.34	Merapi	26/05/2006	-7.54	110.44	1152.17	371.84
43R	24/06/2006	6.3	-0.40	123.23	Karangetang	12/07/2006	2.78	125.40	7406.55	498.41
44R	24/08/2006	6.5	51.15	157.54	Shiveluch	25/12/2006	56.65	161.36	1083.42	592.40
45R	26/12/2006	6.0	48.33	154.86	Kliuchevskoi	14/02/2007	56.06	160.64	Inf	Inf
46R	11/01/2007	6.0	-3.66	127.26	Batu Tara	17/01/2007	-7.79	123.58	Inf	Inf
47R	18/03/2007	6.2	4.59	-78.49	Reventador	26/03/2007	-0.08	-77.66	Inf	Inf
48R	07/05/2007	6.0	-44.95	-80.58	Chaiten	03/05/2008	-42.83	-72.65	Inf	Inf
49R	15/07/2007	6.1	52.46	-168.01	Pavlof	15/08/2007	55.42	-161.89	Inf	Inf
50R	08/08/2007	7.5	-5.86	107.42	Kelut	18/11/2007	-7.93	112.31	Inf	Inf

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Date of Volcanic Response	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
51R	24/10/2007	6.8	-3.90	101.02	Krakatau	27/10/2007	-6.10	105.42	Inf	Inf
52R	01/01/2008	6.3	-5.88	146.88	Rabaul	02/02/2008	-4.27	152.20	425.72	214.90
53R	20/02/2008	6.2	36.29	21.78	Etna	11/05/2008	37.73	15.00	822.63	1056.34
54R	03/03/2008	6.2	-2.18	99.82	Krakatau	15/04/2008	-6.10	105.42	1324.17	179.45
55R	25/05/2008	6.0	56.09	-153.78	Redoubt	23/03/2009	60.49	-152.74	Inf	Inf
56R	08/06/2008	6.4	37.96	21.53	Stromboli	28/06/2008	38.79	15.21	904.71	307.36
57R	28/06/2008	6.1	10.85	91.71	Barren Island	30/06/2008	12.28	93.86	2542.50	940.79
58R	04/08/2008	6.3	-5.92	130.20	Ibu	06/09/2008	1.49	127.63	1280.93	354.42
59R	08/09/2008	6.9	-13.50	166.97	Ambrym	21/10/2008	-16.25	168.12	378.64	221.21
60R	11/10/2008	6.1	19.16	-64.83	Soufriere Hills	03/12/2008	16.72	-62.18	Inf	Inf
61R	16/11/2008	7.4	1.27	122.09	Karangetang	02/12/2008	2.78	125.40	Inf	Inf
62R	22/11/2008	6.3	-4.35	101.26	Slamet	27/04/2009	-7.24	109.21	Inf	Inf
63R	24/11/2008	7.3	54.20	154.32	Kliuchevskoi	24/11/2008	56.06	160.64	1301.06	139.56
64R	06/12/2008	6.4	-7.39	124.75	Rinjani	03/05/2009	-8.42	116.47	Inf	Inf
65R	15/04/2009	6.3	-3.12	100.47	Kerinci	28/04/2009	-1.70	101.26	Inf	Inf
66R	21/04/2009	6.2	50.83	155.01	Sarychev Peak	11/06/2009	48.09	153.20	Inf	Inf
67R	12/09/2009	6.4	10.71	-67.93	Soufriere Hills	11/10/2009	16.72	-62.18	999.85	370.12
68R	10/10/2009	6.0	47.85	152.46	Karymsky	23/10/2009	54.05	159.45	1356.17	374.60
69R	22/10/2009	6.0	6.73	-82.58	Nevado Del Huila	26/10/2009	2.93	-76.03	3219.39	478.28
70R	28/11/2009	6.1	5.33	126.29	Mayon	14/12/2009	13.26	123.69	Inf	Inf
71R	09/12/2009	6.4	-22.15	170.96	Ambrym	10/01/2010	-16.25	168.12	196.29	112.52
72R	10/12/2009	6.3	53.42	152.76	Bezymianny	17/12/2009	55.98	160.59	Inf	Inf
73R	10/12/2009	6.3	53.42	152.76	Kliuchevskoi	10/12/2009	56.06	160.64	442.89	493.07
74R	09/01/2010	6.2	-9.13	157.63	Tinakula	17/01/2010	-10.38	165.80	7107.63	419.94
75R	06/02/2010	6.0	46.84	152.73	Gorely	16/06/2010	52.56	158.03	Inf	Inf
76R	02/04/2010	6.0	-36.23	-72.88	Villarrica	06/04/2010	-39.42	-71.93	1108.26	415.27

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Date of Volcanic Response	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
77R	30/06/2010	6.3	16.40	-97.78	Santa Maria	22/01/2011	14.76	-91.55	489.72	144.08
78R	30/07/2010	6.3	52.50	159.84	Kizimen	10/12/2010	55.13	160.32	Inf	Inf
79R	03/08/2010	6.3	1.24	126.21	Karangetang	16/08/2010	2.78	125.40	143.91	245.87
80R	24/08/2010	6.2	18.80	-107.19	Popocatepetl	23/09/2010	19.02	-98.62	193.07	192.82
81R	25/10/2010	7.8	-3.49	100.08	Krakatau	06/11/2010	-6.10	105.42	Inf	Inf
82R	23/11/2010	6.1	-5.96	148.97	Manam	23/11/2010	-4.08	145.04	141.97	140.58
83R	30/11/2010	6.8	28.35	139.19	Kirishima	26/01/2011	31.93	130.86	Inf	Inf
84R	17/03/2011	6.2	-17.28	167.83	Yasur	19/03/2011	-19.53	169.44	124.04	114.48
85R	01/06/2011	6.3	-37.58	-73.69	Puyehue-Cordón Caulle	08/06/2011	-40.59	-72.12	Inf	Inf

TABLE 5-2 INSTANCES OF DECREASED VOLCANIC ACTIVITY FOLLOWING A TRIGGERING EARTHQUAKE (ORDERED BY DATE OF THE TRIGGERING EARTHQUAKE).

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Date of Volcanic Response	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
1D	26/07/2001	6.4	39.08	24.29	Etna	07/08/2001	37.73	15.00	-52.86	-229.26
2D	22/01/2003	7.5	18.90	-104.06	Colima	25/01/2003	19.51	-103.62	-94.15	-236.64

TABLE 5-3 EARTHQUAKE-VOLCANO INTERACTION CASE STUDIES WHERE NO TRIGGERING WAS OBSERVED FOLLOWING AN EARTHQUAKE (ORDERED BY DATE OF THE TRIGGERING EARTHQUAKE).

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
1NR	25/05/2001	6.3	-7.85	110.04	Krakatau	-6.10	105.42	0.00	13.66
2NR	15/06/2001	6.0	18.81	147.04	Anatahan	16.35	145.67	0.00	0.00
3NR	08/07/2001	6.1	-6.69	152.14	Pago	-5.58	150.52	0.00	0.00
4NR	28/07/2001	6.6	59.00	-155.09	Shishaldin	54.76	-163.97	0.00	0.00
5NR	02/08/2001	6.3	56.22	163.70	Kliuchevskoi	56.06	160.64	0.00	0.00

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
6NR	05/03/2002	7.5	6.02	124.21	Karangetang	2.78	125.40	-67.39	-83.83
7NR	11/04/2002	6.1	-14.43	167.81	Lopevi	-16.51	168.35	0.00	-27.09
8NR	25/05/2002	6.3	53.82	-161.16	Augustine	59.36	-153.43	0.00	0.00
9NR	03/07/2002	6.1	-5.06	147.52	Rabaul	-4.27	152.20	0.00	48.03
10NR	15/08/2002	6.2	-1.26	121.29	Batu Tara	-7.79	123.58	0.00	0.00
11NR	12/10/2002	6.0	15.07	118.42	Mayon	13.26	123.69	0.00	0.00
12NR	15/11/2002	6.6	-55.80	-36.19	Michael	-57.79	-26.46	0.00	-47.81
13NR	21/01/2003	6.4	13.62	-90.85	Pacaya	14.38	-90.60	0.00	0.00
14NR	13/05/2003	6.3	-17.28	167.81	Ambrym	-16.25	168.12	3.15	13.49
15NR	16/06/2003	6.8	55.46	159.93	Shiveluch	56.65	161.36	-26.10	-187.79
16NR	14/08/2003	6.2	38.94	20.62	Etna	37.73	15.00	-100.00	-214.87
17NR	21/09/2003	6.5	19.88	95.63	Barren Island	12.28	93.86	0.00	0.00
18NR	12/11/2003	6.3	33.24	136.98	Sakura Jima	31.59	130.66	0.00	0.00
19NR	05/12/2003	6.6	55.57	165.73	Karymsky	54.05	159.45	-49.79	-96.39
20NR	09/12/2003	6.2	51.33	-179.31	Cleveland	52.83	-169.94	0.00	0.00
21NR	02/03/2004	6.2	11.65	-86.90	Fuego	14.47	-90.88	-15.34	25.34
22NR	25/07/2004	7.3	-2.52	103.92	Merapi	-7.54	110.44	0.00	0.00
23NR	28/08/2004	6.5	-34.92	-70.46	Llaima	-38.69	-71.73	0.00	0.00
24NR	04/10/2004	6.0	14.60	147.09	Pagan	18.13	145.80	0.00	0.00
25NR	18/12/2004	6.2	48.83	156.28	Karymsky	54.05	159.45	-41.02	-21.97
26NR	10/04/2005	6.7	-1.68	99.55	Krakatau	-6.10	105.42	0.00	0.00
27NR	15/06/2005	6.5	-44.89	-80.55	Chaiten	-42.83	-72.65	0.00	0.00
28NR	15/06/2005	6.5	-44.89	-80.55	Villarrica	-39.42	-71.93	18.97	50.74
29NR	11/08/2005	6.1	-22.72	169.73	Yasur	-19.53	169.44	-35.65	-27.95
30NR	30/11/2005	6.4	6.25	124.01	Karangetang	2.78	125.40	0.00	57.61

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
31NR	05/12/2005	6.8	-6.25	29.77	Nyiragongo	-1.52	29.25	67.55	22.00
32NR	08/01/2006	6.7	36.30	23.34	Etna	37.73	15.00	0.00	59.05
33NR	23/01/2006	6.4	-17.36	167.78	Ambrym	-16.25	168.12	0.00	-53.73
34NR	21/05/2006	6.0	1.52	-85.41	Cerro Azul	-0.92	-91.41	0.00	0.00
35NR	26/05/2006	6.3	-7.96	110.34	Rinjani	-8.42	116.47	0.00	0.00
36NR	28/05/2006	6.5	-5.71	151.20	Langila	-5.53	148.42	0.00	-39.07
37NR	17/07/2006	7.7	-9.32	107.33	Kelut	-7.93	112.31	0.00	0.00
38NR	19/07/2006	6.4	-5.51	150.74	Kavachi	-9.02	157.95	0.00	0.00
39NR	07/08/2006	6.8	-15.80	167.82	Yasur	-19.53	169.44	31.15	30.41
40NR	11/08/2006	6.0	18.53	-101.08	Colima	19.51	-103.62	-100.00	-27.09
41NR	11/08/2006	6.0	18.53	-101.08	Popocatepetl	19.02	-98.62	47.86	63.48
42NR	29/09/2006	6.1	10.87	-61.79	Soufriere Hills	16.72	-62.18	-36.57	-78.83
43NR	01/12/2006	6.3	3.39	99.09	Kerinci	-1.70	101.26	0.00	0.00
44NR	30/01/2007	6.6	20.96	144.82	Anatahan	16.35	145.67	0.00	-38.42
45NR	24/02/2007	6.3	-7.03	-80.49	Tungurahua	-1.47	-78.44	-54.93	-42.33
46NR	28/02/2007	6.1	-55.23	-29.11	Mount Belinda	-58.42	-26.33	-70.02	-95.16
47NR	18/06/2007	6.3	-3.57	151.00	Manam	-4.08	145.04	-88.20	-51.58
48NR	16/07/2007	6.8	36.80	134.86	Kirishima	31.93	130.86	0.00	0.00
49NR	08/08/2007	7.5	-5.86	107.42	Ijen	-8.06	114.24	0.00	0.00
50NR	27/11/2007	6.6	-10.95	162.15	Tinakula	-10.38	165.80	0.00	-100.42
51NR	29/11/2007	7.4	14.94	-61.27	Soufriere Hills	16.72	-62.18	-100.00	-120.72
52NR	26/12/2007	6.4	52.56	-168.22	Pavlof	55.42	-161.89	0.00	-85.53
53NR	30/01/2008	6.2	-7.30	127.69	Dukono	1.68	127.88	-74.26	-50.37
54NR	12/02/2008	6.5	16.36	-94.30	Popocatepetl	19.02	-98.62	-18.04	-13.29
55NR	15/04/2008	6.1	13.56	-90.60	Santa Maria	14.76	-91.55	-18.56	-10.79

Event ID	Earthquake Date	Earthquake Magnitude	Earthquake Latitude (˚)	Earthquake Longitude (˚)	Volcano	Volcano Latitude (˚)	Volcano Longitude (˚)	Change in Radiant Flux (%)	β-Statistic
56NR	29/05/2008	6.3	64.01	-21.01	Hekla	63.98	-19.70	0.00	0.00
57NR	01/06/2008	6.3	20.12	121.35	Mayon	13.26	123.69	0.00	0.00
58NR	03/06/2008	6.0	-8.10	120.23	Semeru	-8.11	112.92	11.18	-15.41
59NR	05/07/2008	7.7	53.88	152.89	Alaid	50.86	155.55	0.00	0.00
60NR	24/07/2008	6.2	50.97	157.58	Kizimen	55.13	160.32	0.00	0.00
61NR	28/07/2008	6.0	-10.58	163.10	Bagana	-6.14	155.20	-27.61	-43.74
62NR	26/08/2008	6.4	-7.64	-74.38	Reventador	-0.08	-77.66	36.65	153.05
63NR	16/10/2008	6.7	14.42	-92.36	Fuego	14.47	-90.88	-75.05	49.52
64NR	18/12/2008	6.2	-32.46	-71.73	Puyehue-Cordón Caulle	-40.59	-72.12	0.00	0.00
65NR	25/12/2008	6.3	5.75	125.38	Awu	3.67	125.50	0.00	0.00
66NR	07/09/2009	6.2	-10.20	110.63	Merapi	-7.54	110.44	0.00	0.00
67NR	17/11/2009	6.6	52.12	-131.40	Mount St Helens	46.20	-122.18	0.00	0.00
68NR	28/11/2009	6.1	5.33	126.29	Karangetang	2.78	125.40	-47.23	-26.74
69NR	28/11/2009	6.0	-10.40	118.89	Raung	-8.13	114.04	0.00	0.00
70NR	10/12/2009	6.3	53.42	152.76	Shiveluch	56.65	161.36	-0.50	-10.25
71NR	18/06/2010	6.2	44.45	148.69	Sarychev Peak	48.09	153.20	0.00	-38.42
72NR	12/07/2010	6.3	-22.15	-68.22	Lascar	-23.37	-67.73	0.00	0.00
73NR	23/12/2010	6.4	53.13	171.16	Tolbachik	55.83	160.33	0.00	0.00
74NR	02/01/2011	7.2	-38.36	-73.33	Villarrica	-39.42	-71.93	-54.94	-80.47
75NR	15/02/2011	6.1	-2.50	121.48	Paluweh	-8.32	121.71	0.00	0.00
76NR	16/07/2011	6.0	-33.82	-71.83	Copahue	-37.86	-71.18	0.00	0.00
77NR	04/08/2011	6.1	48.83	154.77	Kliuchevskoi	56.06	160.64	0.00	-191.76
78NR	01/11/2011	6.3	19.83	-109.21	Colima	19.51	-103.62	0.00	-33.23
79NR	14/11/2011	6.3	-0.95	126.91	Karangetang	2.78	125.40	0.00	7.64
80NR	11/12/2011	6.2	-56.01	-28.18	Mount Belinda	-58.42	-26.33	0.00	0.00

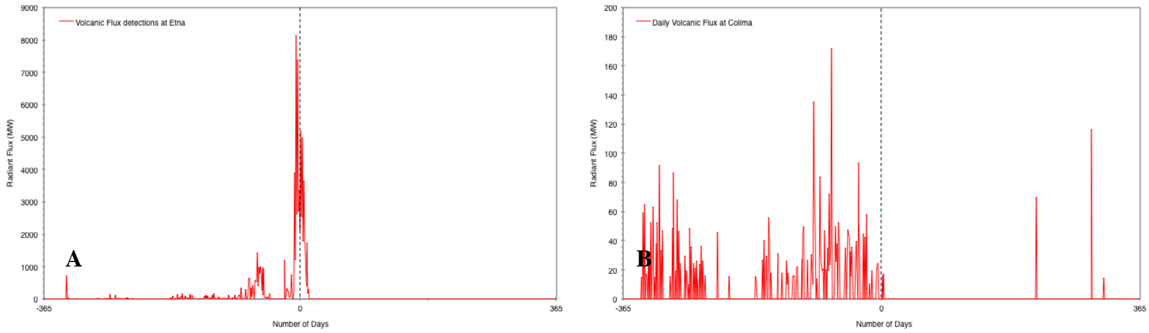


FIGURE 5-4 DECREASES IN ACTIVITY AT A) ETNA, ITALY AND B) COLIMA, MEXICO FOLLOWING A M6.4 AND M7.5 EARTHQUAKE, RESPECTIVELY. ABSENCE OF RADIANT FLUX DETECTIONS ARE EVIDENT FOLLOWING EACH TRIGGERING EARTHQUAKE, DASHED LINE REPRESENTS THE TRIGGERING EARTHQUAKE.

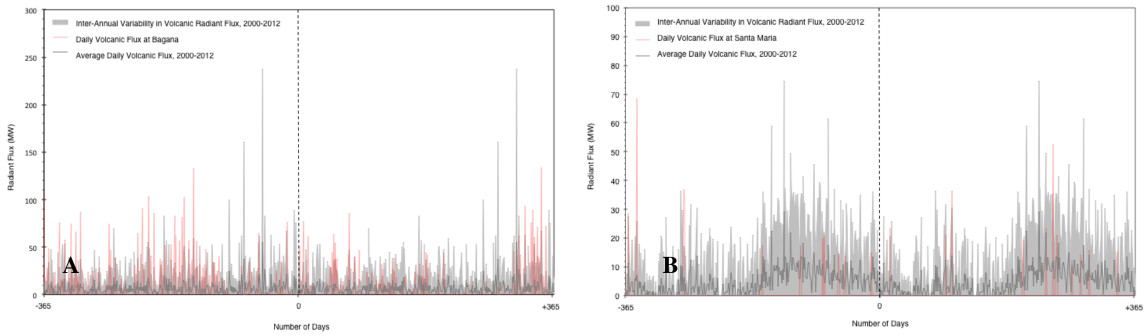


FIGURE 5-5 EXAMPLES OF NON-RESPONSES WHERE $v + 1\sigma$ WERE NOT EXCEEDED FOR A) BAGANA, PAPUA NEW GUINEA AND B) SANTA MARIA, GUATEMALA, DASHED LINE REPRESENTS THE TRIGGERING EARTHQUAKE.

5-2 EARTHQUAKE-VOLCANO INTERACTION EVENT PARAMETERS

For this research, parameters, or characteristics, of the triggering earthquake and responding volcano that were identified to influence triggering by previous research (Table 3-1, pg. 77) were analysed (identified in Appendices IV and V). Each of the regional earthquakes analysed ranged between M6.0-M7.8 (Figure 5-6, Appendix IV). For both the earthquakes that triggered a volcanic response and the earthquakes with no observed response, the majority (82% [70] and 75% [60], respectively) of earthquakes ranged from M6.0-M6.5 with fewer responses being identified following M≥7.0 earthquakes (4 and 7 responses, respectively).

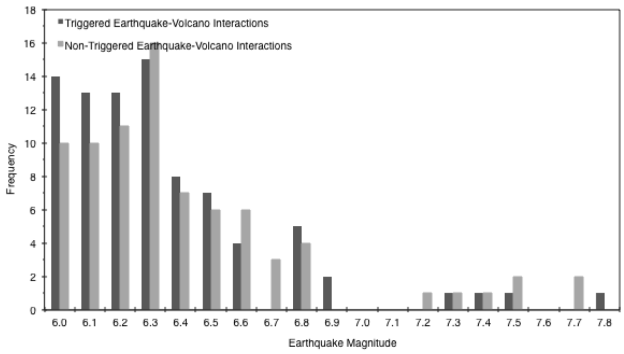


FIGURE 5-6 FREQUENCY HISTOGRAM IDENTIFYING THE NUMBER OF M≥6.0 EARTHQUAKES OBSERVED IN TRIGGERED AND NON-TRIGGERED EARTHQUAKE-VOLCANO INTERACTIONS.

On initial examination of the type of earthquake fault for triggered and non-triggered interactions, Figure 5-7 shows that there is no clear earthquake fault that triggers a response. Reverse (Thrust) and Oblique Reverse are the most common type of fault for both triggered and non-triggered responses accounting for over 75% [130] of the earthquakes analysed (Figure 5-7). Within different regions, however, Figure 5-8 demonstrates that different types of earthquake faults dominate. For example, within Alaska all triggering earthquakes are Thrust faults whereas in Europe all triggering earthquakes are Strike-Slip (Figure 5-8). Alongside this, it was also identified that the majority (62% [104]) of triggered earthquake-volcano interactions were located in an area of compression following the earthquake (Figure 5-9). Eggert and Walter (2009), in particular, stated that further research was required to determine the effect of compression or decompression on volcanic activity triggering. Therefore, based on these findings, it can be suggested that the volcanoes that are most likely to be triggered following an earthquake will be located in an area of increased stress with the characteristics of the region as well as the earthquake fault (i.e. size and direction of fault rupture) playing an important role in triggering following a seismic event.

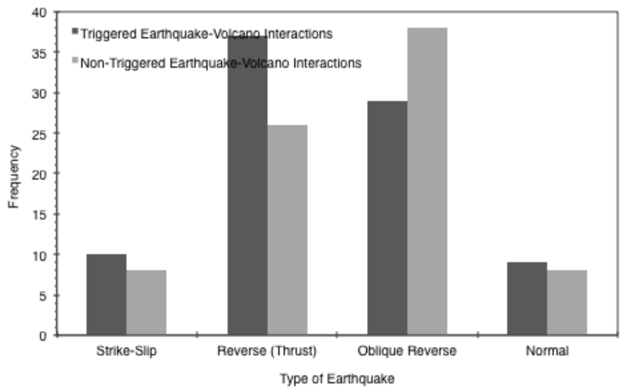


FIGURE 5-7 FREQUENCY HISTOGRAM PRESENTING THE TYPE OF EARTHQUAKE FOR TRIGGERED AND NON-TRIGGERED EARTHQUAKE-VOLCANO INTERACTIONS.

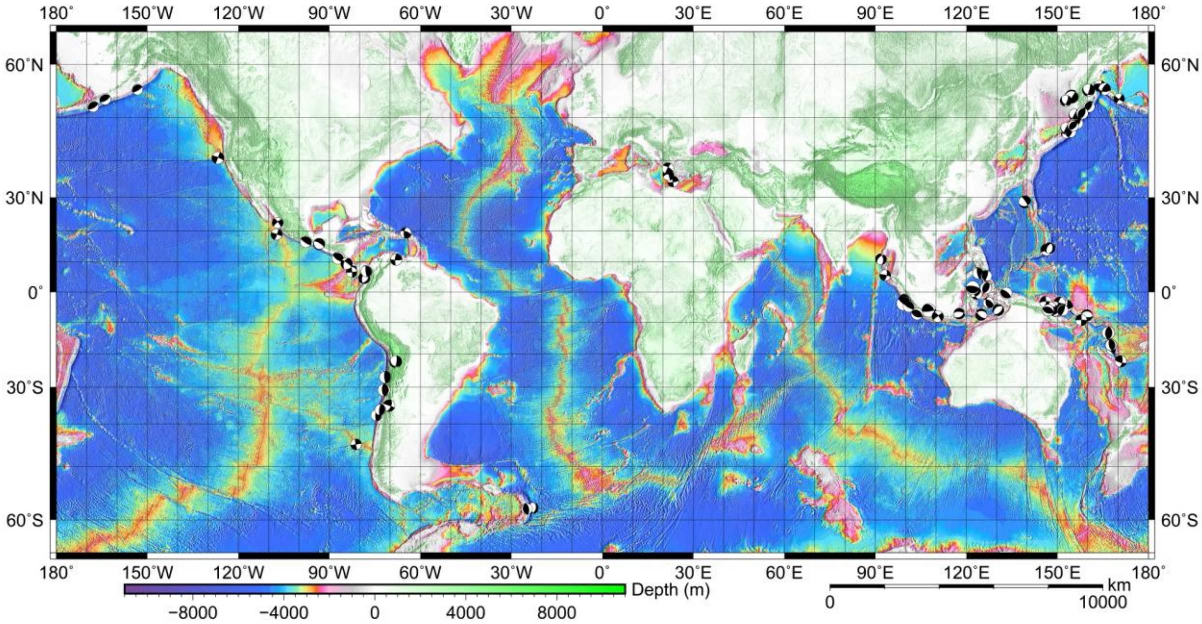


FIGURE 5-8 SPATIAL DISTRIBUTION OF EARTHQUAKE FAULTS FOR ALL TRIGGERED EARTHQUAKE-VOLCANO INTERACTIONS (DERIVED FROM THE GLOBAL CMT CATALOGUE).

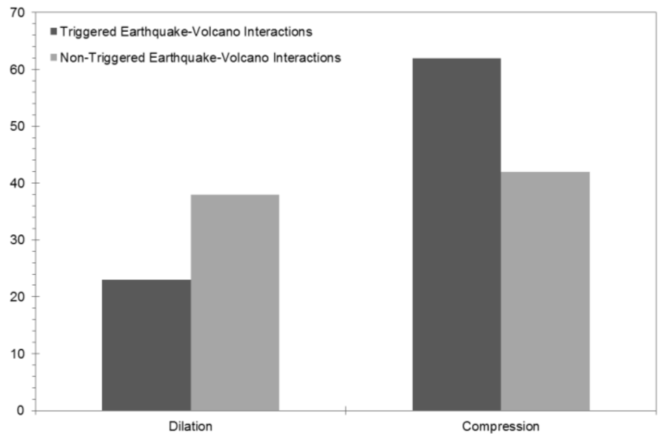


FIGURE 5-9 FREQUENCY HISTOGRAM IDENTIFYING THE LOCATION OF THE VOLCANO IN AN AREA OF COMPRESSION OR DILATATION FOLLOWING AN EARTHQUAKE.

In terms of the responding volcano, Figure 5-10 shows that the majority [23] of triggered responses occurred between 301-400 km and 901-1,000 km away from an earthquake's epicentre whereas responses less than 100 km from an earthquake's source have the lowest proportion of triggered activity. In contrast, the majority of earthquakes that did not initiate a volcanic response occurred at distances between 401 and 700 km. Triggered responses at these distances support triggering by dynamic stress changes, which decay more slowly from an earthquake's source (Manga and Brodsky 2006). In addition, triggering at a global scale (e.g. thermal response of Sierra Negra, Galapagos Islands to 2004 M9.1, Sumatra earthquake 19,000 km away) also provides evidence for triggering by dynamic stress change supporting previous research that suggested that static stress changes at distances of more than a few hundred kilometres are too weak to influence triggering following an earthquake (e.g. Kato *et al*. 2013; Lupi *et al*. 2014).

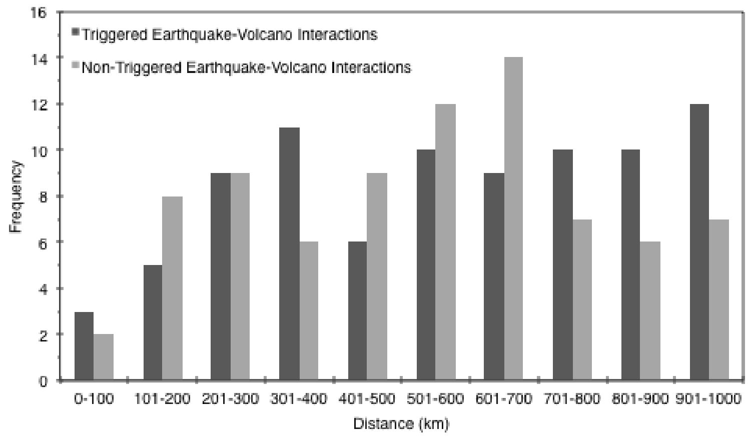


FIGURE 5-10 FREQUENCY HISTOGRAM PRESENTING THE OPTIMUM DISTANCE (KM) FOR VOLCANIC ACTIVITY TRIGGERING FOLLOWING AN EARTHQUAKE.

Figure 5-11 presents boxplots to show the thermal response for each triggered earthquake-volcano interaction. Overall, 4 out of 5 [71] triggered responses occurred within 100 days of a triggering earthquake with 32% [27] occurring within 10 days (Figure 5-11; Appendix IV). For those volcanoes with on-going activity at the time of the earthquake, based on the criteria identified in Chapter 3, volcanic radiant flux had to increase by at least 100% to identify a significant change in activity and, therefore, a potentially triggered response. There were 47 instances where thermal anomalies were detected prior to an earthquake that resulted in a change of volcanic radiant flux of more than 100% in the 365 days following the earthquake (Figure 5-11, Appendix IV). Of these, 87% [41] had thermal anomalies detected at least 100 days prior to an earthquake, which then resulted in increased activity following the event and a return to pre-earthquake levels. Figure 5-12 shows that for those volcanoes with detected thermal anomalies prior to an earthquake, the shortest delay was 1 day. For volcanoes that experienced new activity (38 interactions, i.e. new period of unrest in the 365 following the event), in comparison, the shortest delay was 3 days. Further to this, 85% [23] of volcanoes that experienced new activity following an earthquake only responded once whereas 55% [10] of volcanoes with on-going activity at the time of the earthquake experienced multiple responses (Appendix IV).

The short temporal delays between the triggering earthquake and responding volcano provides evidence to support the theory of ‘clock advance’ where a volcano is already in a

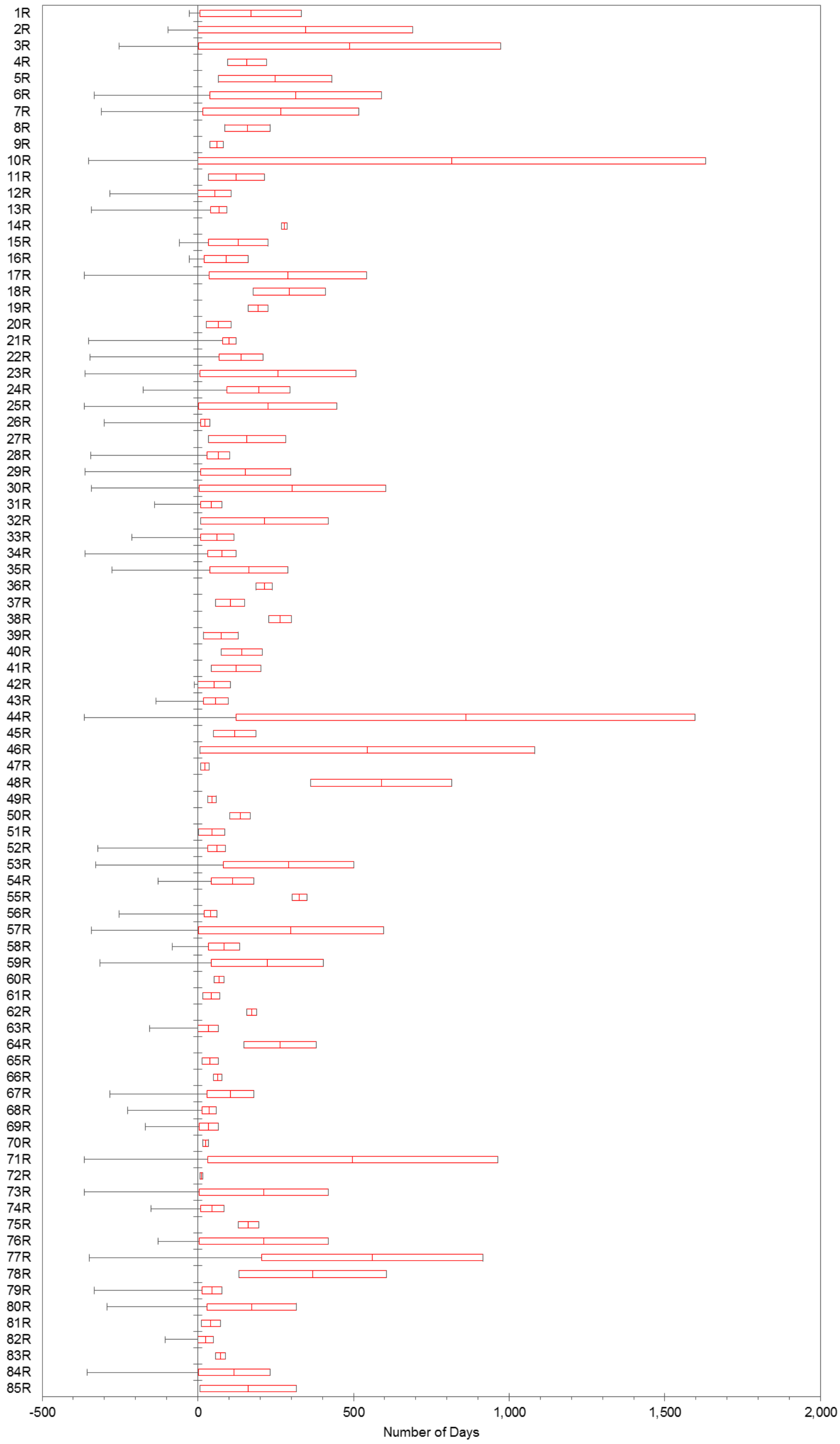


FIGURE 5-11 BOXPLOTS REPRESENTING PERIODS OF TRIGGERED ACTIVITY FOLLOWING AN EARTHQUAKE. GREY BARS INDICATE DETECTED THERMAL ANOMALIES PRIOR TO AN EARTHQUAKE AND RED BOXES INDICATE THE PERIOD OF INCREASED VOLCANIC FLUX FOLLOWING THE EARTHQUAKE. EARTHQUAKE REPRESENTED AS DAY 0.

critical state (i.e. ready to erupt) and the earthquake initiated processes of unrest leading to premature activity (Linde and Sacks 1998; Bebbington and Marzocchi 2011; Prejean and Haney 2014). This indicates that the status of the volcano may also be an important factor and suggests that the processes leading to a response are different depending on whether a volcano is experiencing latent or on-going activity at the time of the earthquake.

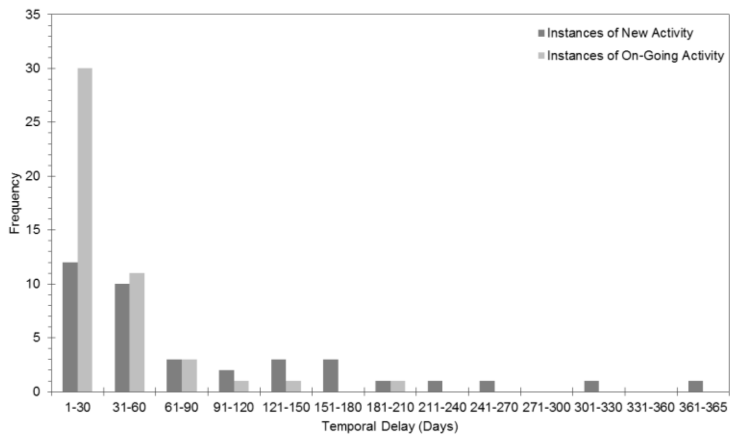


FIGURE 5-12 FREQUENCY HISTOGRAM PRESENTING THE TEMPORAL DELAY BETWEEN THE TRIGGERING EARTHQUAKE AND RESPONDING VOLCANO FOR NEW AND ON-GOING ACTIVITY.

Based on the responses identified in Figure 5-11, Figure 5-13 presents the typical response for volcanoes with new (Figure 5-13a) and on-going (Figure 5-13b) activity following an earthquake. For new periods of thermal unrest, there is a short delay (between 3 and 362 days) before new thermal activity is detected with heightened activity lasting between 31 and 361 days in 66% of cases (Figure 5-13a; Figure 5-14). This type of response provides evidence to support suggestions that volcanoes need to be in a critical state (i.e. ready to erupt) for a response to occur (Linde and Sacks 1998; Hill *et al*. 2002; Marzocchi and Bebbington 2012). In contrast, for volcanoes with on-going activity at the time of the triggering earthquake there is an increase in volcanic radiant flux for the first six months, which then decreases to pre-earthquake levels for the remainder of the period (Figure 5-13b). In general, the period of heightened activity for volcanoes with on-going activity is shorter with activity lasting between 31 and 300 days after the time of the earthquake in the majority (62% [29]) of cases (Figure 5-11; Figure 5-14). This supports previous suggestions by Marzocchi *et al*. (2002) who indicated that volcanoes with new activity following an earthquake trigger would experience increased activity until a new equilibrium is met.

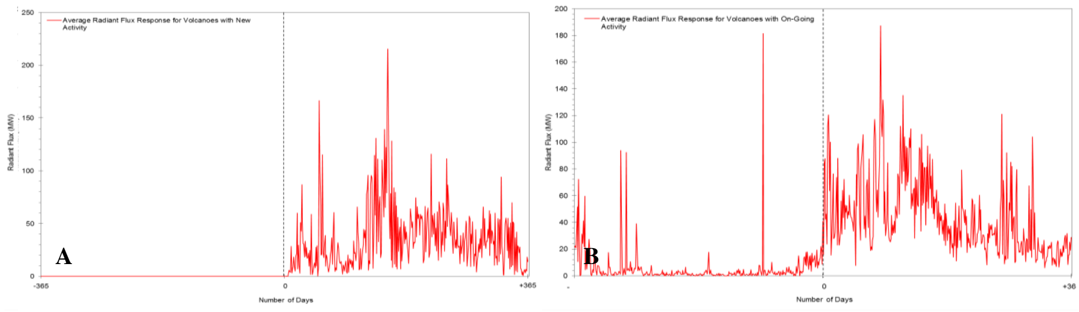


FIGURE 5-13 AVERAGE VOLCANIC RESPONSE (BASED ON THE AVERAGE FOR ALL VOLCANOES) FOLLOWING AN EARTHQUAKE TRIGGER FOR A) NEW VOLCANIC ACTIVITY AND B) ON-GOING ACTIVITY. DASHED LINE REPRESENTS THE TRIGGERING EARTHQUAKE.

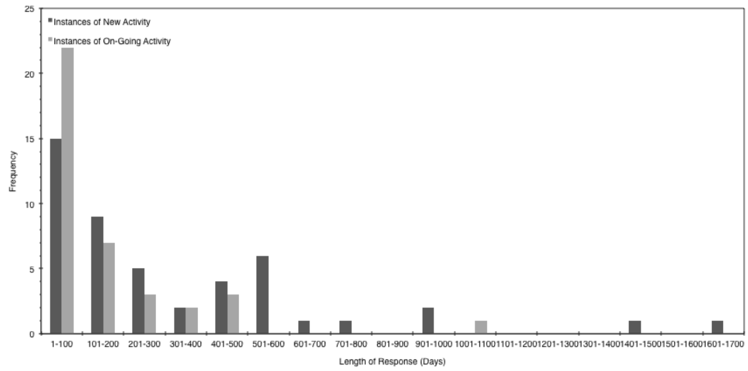


FIGURE 5-14 FREQUENCY HISTOGRAM TO SHOW THE LENGTH OF RESPONSE FOR PERIODS OF NEW AND ON-GOING ACTIVITY FOLLOWING AN EARTHQUAKE TRIGGER.

5-3 ASSESSMENT OF EARTHQUAKE-VOLCANO INTERACTIONS AND EVENT PARAMETERS

Using the earthquake-volcano interactions in Tables 5-1 and 5-3 and the associated event parameters identified in Appendices IV and V, machine learning and statistical analyses were employed to assess the significance of earthquake-volcano interactions and identify controlling parameters. Firstly, the average number of volcanoes experiencing thermal unrest, N_b and N_a, for triggered and non-triggered responses is shown in Figure 5-15. Table 5-4 shows that for all triggered interactions, the number of volcanoes experiencing thermal unrest after an earthquake, N_a, is statistically different to the number of volcanoes experiencing thermal unrest before an earthquake, N_b (*t-stat* -55.21, p 2.9 x 10^{-179} (*<0.05)*).

This research also examined the significance of the change in the number of days experiencing thermal unrest, N_b to N_a, as compared to cases of non-triggered activity. Figure 5-15 shows that for all instances of non-triggered activity (4,141 instances where an earthquake is located within 1,000 km to a volcano and change in the number of erupting volcanoes is assessed ±365 days) the average rate of thermal unrest remained constant before and after, N_b and N_a, the event whereas for all instances of triggered activity, the average number of erupting volcanoes more than doubles. Using a two-factor analysis of variance (ANOVA) test (Table 5-5), the difference between change in the number of erupting volcanoes N_b and N_a for triggered and non-triggered activity was compared. Table 5-5 shows that on the basis of the *p*-value (Interaction - 0.00 < 0.05), there are significant differences in the observed responses for triggered and non-triggered activity. As a result, it can be concluded that on basis of the *p*-value and the *f*-value (3,504 > *f-critical* 3.85) the average number of erupting volcanoes for triggered activity is statistically different to periods where no response was experienced. While assessments of the number of erupting volcanoes before and after an earthquake have been conducted previously (Linde and Sacks 1998; Manga and Brodsky 2006; Lemarchand and Grasso 2007), the statistical significance of this change has not been examined and comparisons to instances where no activity was triggered have not been made. The results of this thesis, therefore, have important implications for the identification of triggered earthquake-volcano interactions demonstrating a statistically significant change in activity as well as providing evidence to refute suggestions that these interactions may only reflect temporal coincidences.

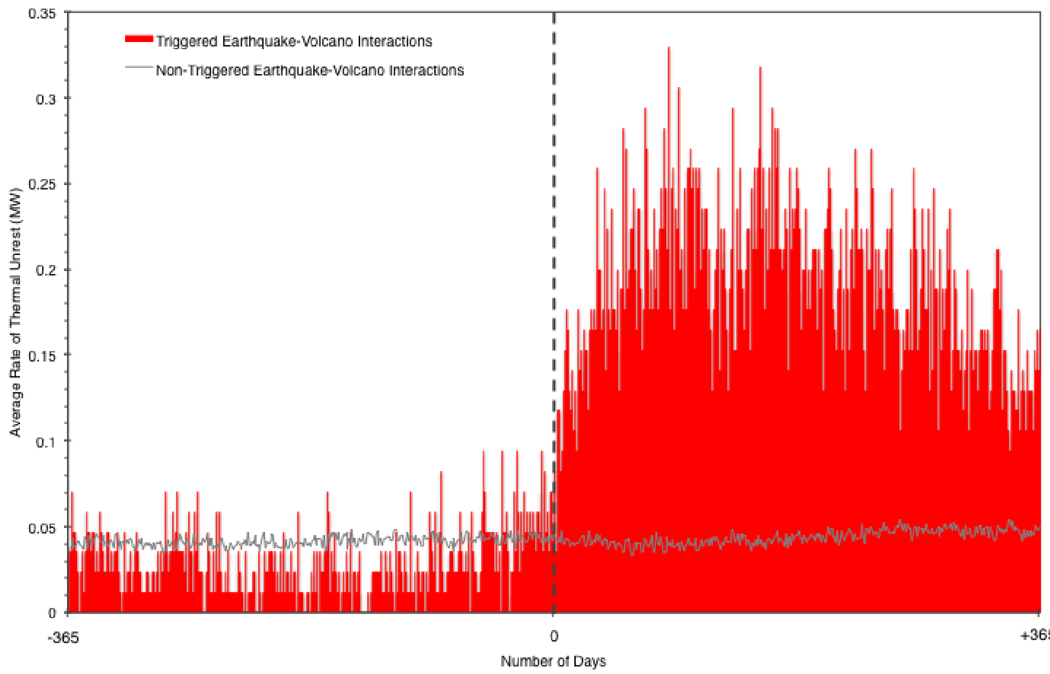


FIGURE 5-15 AVERAGE RATE OF THERMAL UNREST FOR TRIGGERED RESPONSES (RED COLUMNS) AND NON-TRIGGERED RESPONSES (GREY LINE) ±365 DAYS CENTRED ON THE EARTHQUAKE.

TABLE 5-4 *T*-TEST TO COMPARE CHANGE IN THE NUMBER OF VOLCANOES EXPERIENCING THERMAL UNREST N_b TO N_a.

	Variable 1
t-stat	-55.21
p-value	2.9×10^{-179}

TABLE 5-5 ANALYSIS OF VARIANCE (ANOVA) TEST FOR CHANGE IN THE NUMBER OF ERUPTING VOLCANOES N_b AND N_a FOR TRIGGERED AND NON-TRIGGERED ACTIVITY.

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F-critical*
Change Centred on the Earthquake (Sample)	2.39	1.00	2.39	3,713.80	0.00	3.85
Response or Non-Response (Columns)	1.58	1.00	1.58	2,449.45	0.00	3.85
Interaction	2.25	1.00	2.25	3,504.60	0.00	3.85
Within	0.94	1,460.00	0.00			

Alongside this, to test if the same correlations could be produced by chance, this research examined the significance of the change in the number of volcanoes experiencing thermal unrest based on a randomised set of earthquake and volcanic hotspot data. Table 5-6 shows that on the basis of these dummy datasets the same results cannot be produced by chance (*t-stat* 0.09, *p-value 0.93 (>0.05)*). These findings are also supported by cross-correlations of dummy datasets by Delle Donne *et al*. (2010) who showed that the response proportions are similar for all earthquake magnitudes based on a randomised dataset compared to an increasing response proportion for triggered interactions.

TABLE 5-6 *T*-TEST TO COMPARE CHANGE IN THE NUMBER OF VOLCANOES EXPERIENCING THERMAL UNREST, N_b TO N_a, BASED ON RANDOMISED EARTHQUAKE AND VOLCANO DATASETS.

	Variable 1
t-stat	0.09
p-value	0.93

Machine learning assessments were then performed to assess patterns of response based on the interactions identified in this research. As identified in Chapter 3, depending on the objective field of the model, *y*, triggered and non-triggered interactions were examined and the data split into training and test samples (Table 5-7, Appendix VI details the division of data into training and test subsets). The Interaction (response or non-response) model was shown to have the greatest accuracy (78%) identifying whether a volcano would experience triggered or non-triggered activity following an earthquake. In contrast, the models that examined a volcano's response characteristics (response only interactions:- change in volcanic radiant flux, temporal delay and length of response) reported the lowest model accuracies, therefore, showing that although these parameters are a reliable indicator of volcanic activity triggering, they do not reliably indicate the characteristics of triggered responses. Overall, parameters such as time since last eruption, distance, azimuth to responding volcano, tectonic plate of the earthquake and incoming wave direction (Table 5-8) were identified to have the largest influence over response characteristics. However, particularly low R^2 values (Table 5-7 – 0.03, -0.16 and -0.08, respectively) indicate that the parameters assessed are not a good indicator of a volcano's response.

TABLE 5-7 EARTHQUAKE-VOLCANO INTERACTIONS ANALYSED AS PART OF MACHINE LEARNING ANALYSES INCLUDING OBJECTIVE FIELD IDENTIFIED AND MODEL ACCURACY. APPENDIX VI DETAILS THE DIVISION OF THE DATA INTO TRAINING AND TEST DATA.

Objective Field	Model Accuracy (% or R^2)
Interaction (Response or No Response)	78%
Change in Volcanic Radiant Flux (%)	0.03
Temporal Delay (Days)	-0.16
Length of Response (Days)	-0.08

TABLE 5-8 MODEL OUTCOMES FOR RESPONSE ONLY INTERACTIONS WHERE RESPONSE CHARACTERISTICS ARE THE OBJECTIVE FIELD.

Objective Field, *y*	Parameters of Importance	Model Accuracy (R^2)
Change in Volcanic Radiant Flux	Time Since Last Period of Volcanic Activity – 52.00% Type of Earthquake Fault – 13.33% Distance – 9.51% Tectonic Plate of Earthquake – 5.74% Incoming Earthquake Wave Direction – 5.19%	0.03
Temporal Delay	Time Since Last Period of Volcanic Activity – 44.52% Earthquake Azimuth to Volcano – 14.56% Tectonic Plate of Earthquake – 8.59% Region of Volcano – 6.61% Incoming Earthquake Wave Direction – 4.47%	-0.16
Length of Response	Distance – 35.60% Earthquake Azimuth to Volcano – 19.13% Incoming Earthquake Wave Direction – 15.19% Tectonic Plate of Earthquake – 6.90% Region of Volcano – 4.96%	-0.08

Table 5-9 reports the overall outcome for the Interaction (response or non-response) model, which identifies the importance of each parameter on a volcano's response (Table 5-9 a & c) and its accuracy (Table 5-9b) based on the evaluation of test data. Earthquake rupture length has the largest influence (36.12%) on a volcano's response with additional earthquake fault characteristics (strike, magnitude, dip and depth) also having a large impact (≥5.68%) on the accuracy of the model. Volcanic parameters (e.g. magma composition, surrounding volcanic geology and volcano type), in comparison, are the least important factors indicating an influence of less than 2.73% each. The associated Phi co-efficient (Table 5-9b) reports the correlation between the observed and predicted responses. Based on the patterns identified, this model is shown to have an accuracy of 0.64 in predicting a volcano's response reporting interactions (response or non-response) of more than random chance (0) but less than perfect prediction (+1).

Figures 5-16 and 5-17 display two examples of subsets of the overall tree produced for the Interaction model. Figure 5-16 demonstrates a subset of the model for responses in the Philippines and Figure 5-17 presents the conditions that would not initiate a response in the Japanese Arc. In Figure 5-16, 25 instances of triggered responses were identified accounting for 21.74% of the data and, in Figure 5-17 this pattern of non-response accounted for 8.70% of the data. In both trees it is evident that variations in the parameters controlling a volcano's response differ depending on the geographic region with parameters related to the triggering earthquake present in both models. Despite this, examination of the model based on individual geographic regions did not identify any clear patterns or controlling parameters.

TABLE 5-9 INTERACTION (RESPONSE OR NON-RESPONSE) MODEL OUTCOME - (A) IMPORTANCE OF EVENT PARAMETERS, (B) MODEL ACCURACY AND (C) IMPORTANCE OF EVENT PARAMETERS DEMONSTRATED GRAPHICALLY.

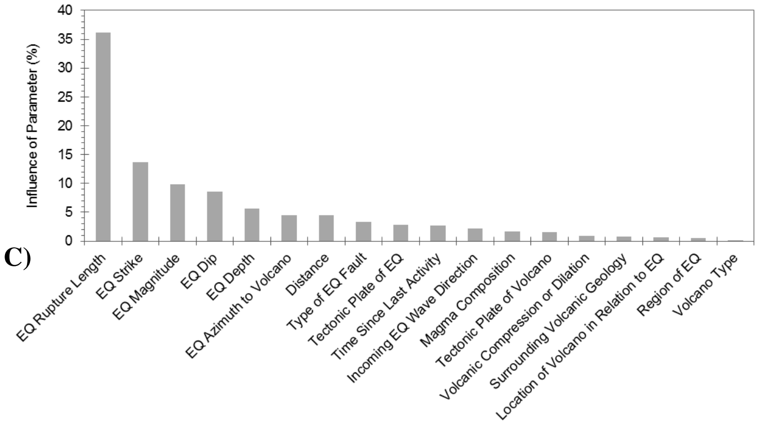
A) Objective Field = Interaction (Response or Non-Response)

Field§	Parameter	Influence of Parameter (%)
1	Earthquake Rupture Length	36.12
2	Earthquake Strike	13.73
3	Earthquake Magnitude	9.79
4	Earthquake Dip	8.54
5	Earthquake Depth	5.68
6	Earthquake Azimuth to Volcano	4.53
7	Distance	4.45
8	Type of Earthquake Fault	3.33
9	Tectonic Plate of Earthquake	2.82
10	Time Since Last Activity	2.73
11	Incoming Earthquake Wave Direction	2.12
12	Magma Composition	1.72
13	Tectonic Plate of Volcano	1.58
14	Volcanic Compression or Dilatation	0.87
15	Surrounding Volcanic Geology	0.80
16	Location of Volcano in Relation to Earthquake	0.59
17	Region of Earthquake	0.48
18	Volcano Type	0.12

§ Only parameters that are identified to influence the model are shown

B)	Non-Response	Response	Actual	Recall (%)	Phi
Non-Response	22	0	22	100.00	0.64
Response	11	17	28	60.71	0.64
Predicted	33	17	50	80.36	0.64
Precision (%)	66.67	100.00	83.33	78.00	

C)



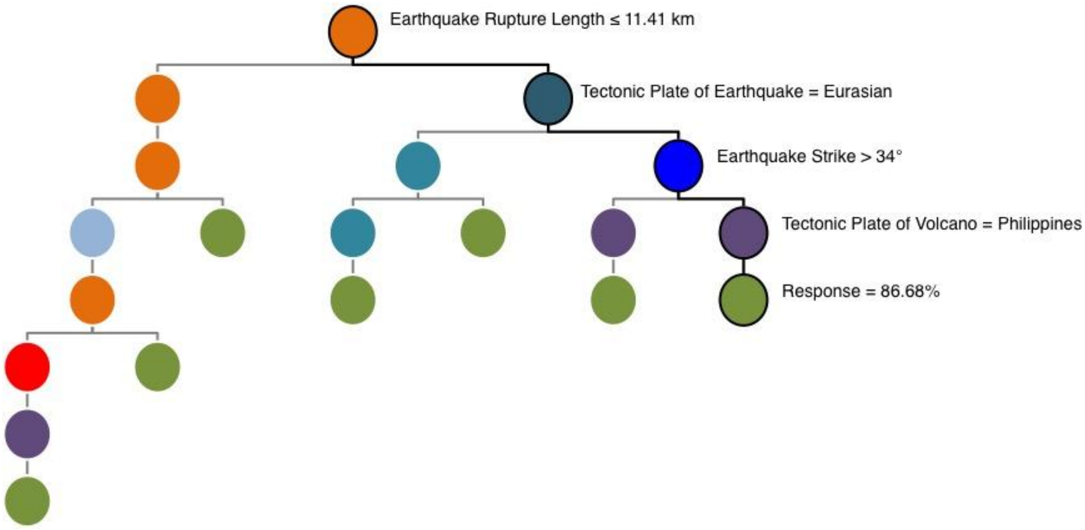


FIGURE 5-16 EXAMPLE OF DECISION TREE MODEL FOR RESPONSE INTERACTIONS IN THE PHILIPPINES. BASED ON THE CONDITIONS IDENTIFIED: EARTHQUAKE RUPTURE LENGTH SMALLER THAN OR EQUAL TO 11.41 KM, EARTHQUAKE LOCATED ON THE EURASIAN PLATE, AN EARTHQUAKE STRIKE OF MORE THAN 34° AND THE VOLCANO LOCATED ON THE PHILIPPINES PLATE; A RESPONSE WOULD BE EXPECTED (86.68% CONFIDENCE).

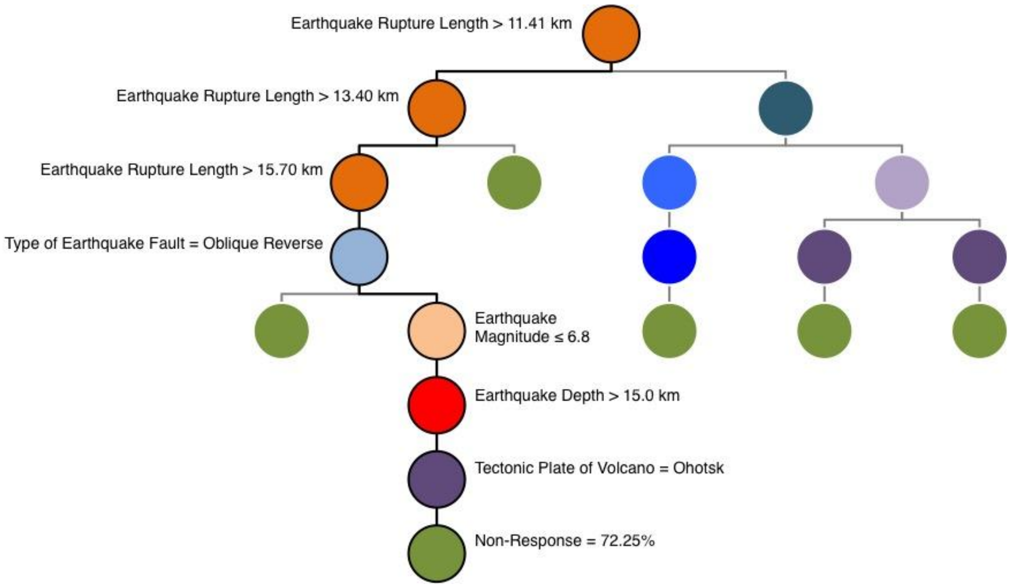


FIGURE 5-17 EXAMPLE OF DECISION TREE MODEL FOR NON-RESPONSE INTERACTIONS IN THE JAPANESE ARC. BASED ON THE CONDITIONS IDENTIFIED: EARTHQUAKE RUPTURE LENGTH BIGGER THAN 15.70 KM, AN OBLIQUE REVERSE EARTHQUAKE FAULT, AN EARTHQUAKE MAGNITUDE OF LESS THAN OR EQUAL TO 6.8, AN EARTHQUAKE DEPTH OF MORE THAN 15.0 KM AND THE VOLCANO LOCATED ON THE OKHOTSK PLATE, A RESPONSE WOULD NOT BE EXPECTED (72.27% CONFIDENCE).

In order to assess the ability to predict volcanic activity following an earthquake based on the parameters identified to influence the relationship, predictions using case studies from previous earthquake-volcano interactions research and post-2012 instances of M≥6.0 earthquakes were performed using the Interaction (response or non-response) model. Table 5-10 details the triggering earthquake, responding volcano and observed and predicted responses of each of these case studies (Appendix VII details the parameters associated with each earthquake-volcano interaction examined). For predictions using case studies from previous research, the model accurately identified whether triggering would occur for 100% of interactions assessed reporting confidences between 47.59%-77.92% (Table 5-10). Critically, it must be noted that where the observed response included thermal activity the model accurately identified whether a response would be expected but for instances where seismicity or deformation were recorded with no thermal response, the model identified that the volcano would not be triggered. In this regard, it can be suggested that the parameters that influence a seismic or deformational response may be different to the parameters that lead to thermal unrest. Therefore, providing further evidence to support the ability of earthquakes to influence the type of response following an earthquake as well as whether a volcano will respond. For post-2012 MODVOLC detected responses, however, only 50% of responses were accurately predicted (accuracy – 59.12-72.25%, Table 5-10). In these cases, the model predicted a response based on the parameters identified but when the associated MODVOLC data was examined no increases in thermal activity were identified. While it is possible that periods of unrest such as seismicity or volcanic deformation resulted from these earthquakes, this thesis did not examine these types of responses. Importantly, however, during this stage of the research some parameters were omitted to assess the ability of the model to predict a response based on a limited number of parameters. Considering this, it is possible that one (or more) of these parameters (tectonic plate of earthquake's location, magma composition, surrounding volcanic geology or the location of the volcano in relation to the earthquake) are key in influencing a volcano's response.

TABLE 5-10 PREDICTED RESPONSES BASED ON INTERACTION (RESPONSE OR NON-RESPONSE) FOR PREVIOUS EARTHQUAKE-VOLCANO INTERACTIONS RESEARCH AND POST-2012 CASE STUDIES.

Prediction ID	Source of Earthquake-Volcano Case Study	Earthquake Date	Earthquake Magnitude	Volcano	Observed Response	Predicted Model Response	Confidence (%)
1P	Battaglia *et al*. 2012	09/04/2008	7.3	Yasur	No Response	No Response	72.96
2P	De la Cruz Reyna *et al*. 2010	15/06/1999	7.0	Popocatepetl	Increased Seismicity and Volcanic Explosion	Response	65.02
3P	Delle Donne *et al*. 2010	09/01/2004	6.3	Langila	Increased MODVOLC Activity	Response	77.18
4P	Fujita *et al*. 2013	11/03/2011	9.0	Fuji	Volcanic Seismicity but No Eruption	No Response	47.59
5P	Harris and Ripepe 2007	26/05/2006	6.4	Merapi	Increased Thermal Activity	Response	63.35
6P	Harris and Ripepe 2007	27/05/2006	6.4	Semeru	Increased Thermal Activity	Response	70.82
7P	Power *et al*. 2001	06/12/1999	7.0	Katmai	Increased Seismicity	No Response	58.50
8P	Pritchard *et al*. 2013	27/02/2010	8.8	Cerro Azul	Volcanic Deformation	No Response	48.31
9P	Cannata *et al*. 2010	08/01/2006	6.8	Etna	Volcanic Seismicity and Delayed Eruption	Response	77.92
10P	Hill *et al*. 1995	28/06/1992	7.3	Long Valley Caldera	Volcanic Seismicity	No Response	67.44
11P	Post-2012	31/01/2013	6.1	Tinakula	No Thermal Activity	Response	72.25
12P	Post-2012	08/02/2013	6.8	Ambrym	No Thermal Activity	No Response	71.90
13P	Post-2012	21/05/2013	6.1	Gorely	No Thermal Activity	Response	59.12
14P	Post-2012	21/08/2013	6.2	Popocatepetl	No Thermal Activity	Response	71.71
15P	Post-2012	04/09/2013	6.5	Pavlof	No Thermal Activity	No Response	64.47
16P	Post-2012	30/10/2013	6.2	Villarrica	No Thermal Activity	No Response	60.37
17P	Post-2012	30/10/2013	6.2	Puyehue-Cordón Caulle	No Thermal Activity	Response	60.37
18P	Post-2012	02/03/2014	6.5	Kirishima	No Thermal Activity	No Response	59.82
19P	Post-2012	19/04/2014	6.6	Bagana	No Thermal Activity	No Response	70.76
20P	Post-2012	23/08/2014	6.4	Cerro Azul	No Thermal Activity	Response	69.34

Further examinations consisted of correlating the parameters that exert the greatest influence on the relationship between earthquakes and volcanic activity to a volcano's response characteristics to determine their significance and identify primary and secondary controlling parameters. Table 5-11 presents the results of these correlations, grouped by field of importance, alongside comparisons of response parameters. Overall, there are no statistically significant relationships between these parameters indicating that no individual parameter identified in this research controls the characteristics of a volcano's response. Therefore, it can be concluded that a combination of parameters contributes towards the relationship between earthquakes and volcanic activity rather than one controlling parameter. In addition, while an earthquake may be capable of modifying a volcano's response characteristics as suggested by Walter and Amelung (2007) and Watt *et al*. (2009), the parameters assessed do not affect the characteristics of response and is due to other underlying factors not examined in this thesis. Appendix VIII presents additional multiple regression analyses, however, this model reported an absence of any significant predictor values.

TABLE 5-11 CORRELATIONS (R^2) OF THE MAIN PARAMETERS IDENTIFIED TO INFLUENCE THE RELATIONSHIP BETWEEN EARTHQUAKES AND VOLCANIC ACTIVITY.

Parameter 1	Parameter 2	R^2
Earthquake Rupture Length	Temporal Delay	-0.0049800
Earthquake Rupture Length	Length of Response	-0.0139800
Earthquake Rupture Length	Distance	-0.0000077
Earthquake Strike	Temporal Delay	0.0029300
Earthquake Strike	Length of Response	-0.0201100
Earthquake Strike	Distance	0.0036200
Earthquake Magnitude	Temporal Delay	-0.0056500
Earthquake Magnitude	Length of Response	-0.0079800
Earthquake Magnitude	Distance	-0.0000015
Earthquake Dip	Temporal Delay	0.0002000
Earthquake Dip	Length of Response	0.0065000
Earthquake Dip	Distance	0.0072900
Earthquake Depth	Temporal Delay	-0.0038700
Earthquake Depth	Length of Response	-0.0089300
Earthquake Depth	Distance	0.0078900
Distance	Temporal Delay	0.0221800
Distance	Length of Response	-0.0013600
Temporal Delay	Length of Response	-0.0021000

5-4 SPATIAL ANALYSES OF EARTHQUAKE-VOLCANO INTERACTIONS

In terms of triggered earthquake-volcano interactions, this thesis observed an overall response rate of 28% [calculated from a total of 307 eruptions during the study period]. To further assess the strength of the interactions at different spatial scales, a volcano's individual response proportion was calculated as well as examining the strength of the relationship within different regions. Figure 5-18 presents the response proportion of each volcano by determining the number of observed eruptions during the study period as compared to the number of eruptions that were triggered following an earthquake. The response proportion per region is also displayed which depicts the total number of eruptions in the region as compared to the total number of triggered eruptions.

Figure 5-18 shows that an individual volcano's response proportion ranged between 0%, where there were no instances of volcanic activity following an earthquake, and 100%. Volcanoes with the highest response proportions are located within Alaska, Kamchatka-Mainland Asia, Indonesia and Southern America while the volcanoes with the lowest response proportion are located within Mexico-Central America and Mediterranean-Western Asia. Of the volcanoes that exhibited multiple responses, Kliuchevskoi, Russia experienced the most instances of triggered activity with 5 of the 7 (71% response proportion) periods of thermal unrest observed at the volcano being related to an earthquake trigger. This suggests that certain volcanoes are more prone to triggering following an earthquake. Although this has been noted previously (e.g. Prejean *et al*. 2004; Manga and Brodsky 2006; Hill-Butler 2012), on the analysis of earthquake and volcano parameters this research shows that those volcanoes with on-going activity during the period are more likely to exhibit multiple responses than volcanoes that have latent activity (i.e. no thermal activity in the year preceding an earthquake) and experience new activity following triggering.

On a regional scale, Figure 5-18 also shows that certain volcanoes or regions are more likely to respond. With the exception of South America, regions within the Pacific Ring of Fire (Alaska, Japan-Taiwan-Marianas, Kamchatka-Mainland Asia, Kuril Islands, Indonesia, Melanesia-Australia and Philippines-South East Asia) exhibit the strongest responses to an earthquake trigger whereas regional response proportion of less than 25% were observed in Antarctica and Mediterranean-Western Asia. This corresponds with the findings of Eggert and Walter (2009) who identified high correlation coefficients between eruption time and distance in Indonesia, Japan-Taiwan-Marianas and New Zealand-Fiji. Previously, 3-4 periods of unrest have been identified following triggering in South America (Watt *et al*. 2009); however, at a global scale this research identified a decrease in global volcanic activity and, at a regional scale, this thesis identified response proportions of 22.22%. The cause of these small response proportions could be due to two main factors: 1) responses within these regions result in periods of unrest (e.g. volcanic seismicity or deformation) not measured in this thesis or, 2) the conditions suggested to influence a volcano's response not being met following earthquakes in South America during the study period.

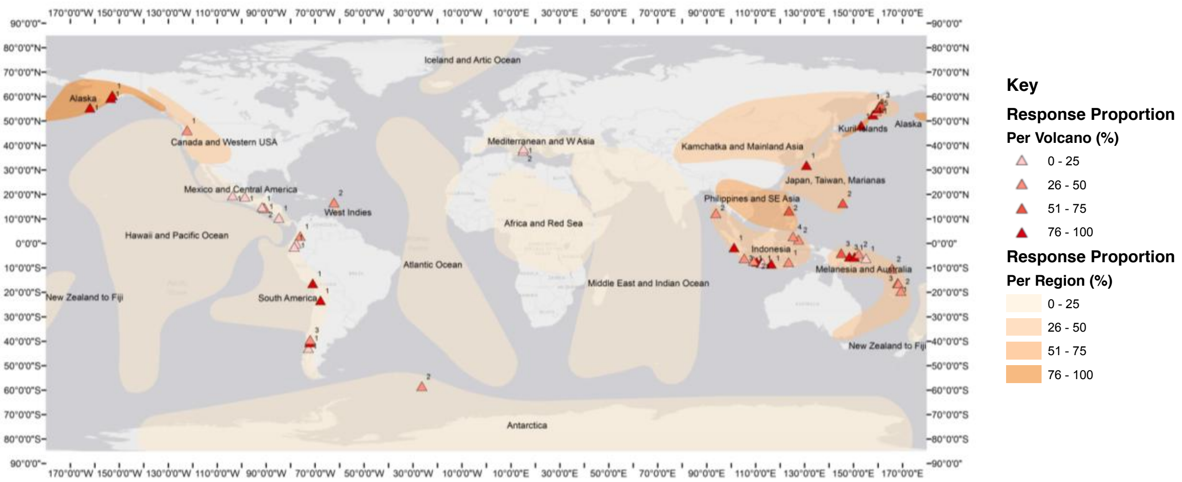


FIGURE 5-18 RESPONSE PROPORTION OF ALL VOLCANOES THAT EXPERIENCED THERMAL UNREST, 2000-2012. WITHIN THE MAP THE RESPONSE PROPORTION OF EACH INDIVIDUAL EARTHQUAKE-VOLCANO INTERACTION AS WELL AS REGIONAL RESPONSE PROPORTIONS ARE PRESENTED.

Alongside this, the spatial distribution of triggered and non-triggered earthquake-volcano interactions was also examined in order to assess if there was a stronger spatial relationship rather than within different regions. Figures 5-19, 5-20 and 5-21 present a comparison of the spatial distribution of response and non-response case studies where the earthquake was normalised to 0° latitude, 0° longitude. Figure 5-19 displays the spatial location of earthquake-volcano interactions while Figure 5-20 presents a polarised plot of the earthquake azimuth and distance to responding volcano and Figure 5-21 presents the spatial distribution of earthquake-volcano interactions as classified by earthquake fault type. Overall, there are no strong spatial distributions between the triggering earthquake and responding volcano. Within Figures 5-19 and 5-20, however, there are small clusters where volcanoes with multiple responses are located. This indicates that, rather than triggering patterns at a regional scale, earthquake-volcano interactions at individuals volcanoes have a stronger relationship therefore supporting the findings of Bebbington and Marzocchi (2011) who suggested that triggering is based on the individual volcano following the identification of statistically significant relationships at 7 volcanoes but the absence of any significant relationship within Indonesia as a whole.

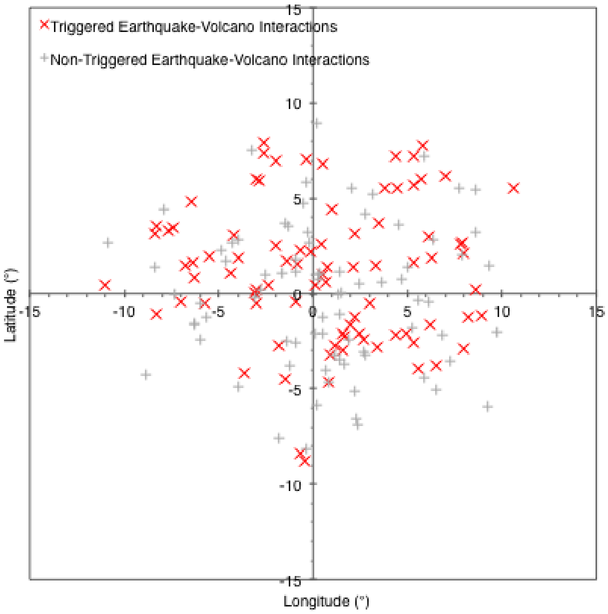


FIGURE 5-19 SPATIAL DISTRIBUTION OF TRIGGERED AND NON-TRIGGERED EARTHQUAKE-VOLCANO INTERACTIONS WHERE THE EARTHQUAKE IS NORMALISED TO 0° LATITUDE, 0° LONGITUDE.

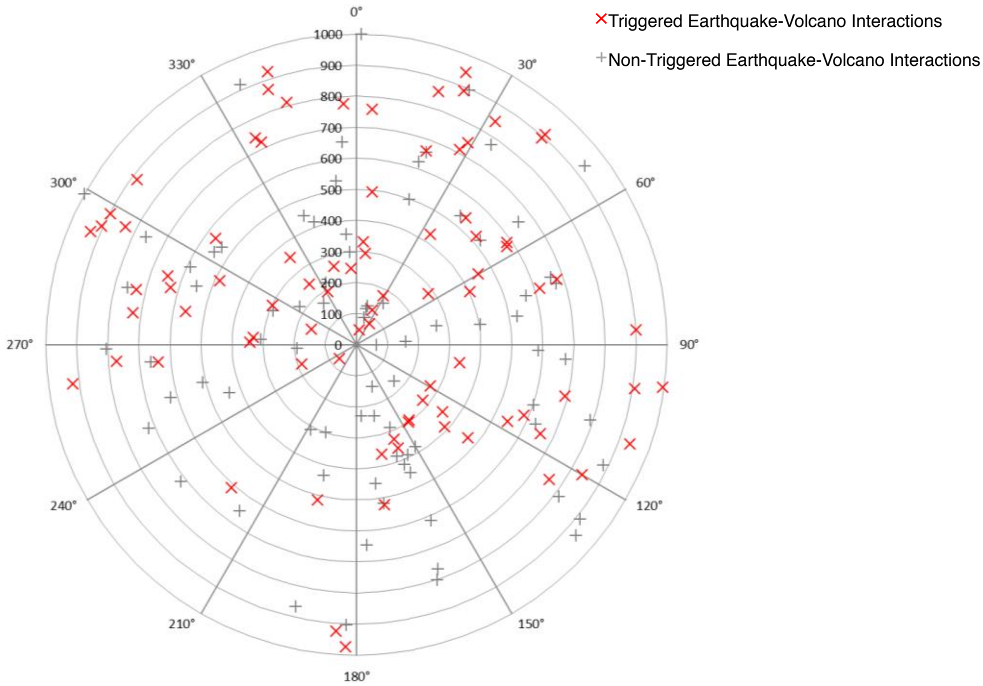


FIGURE 5-20 EARTHQUAKE AZIMUTH TO RESPONDING VOLCANO AS COMPARED TO DISTANCE (KM) (POLAR AXIS).

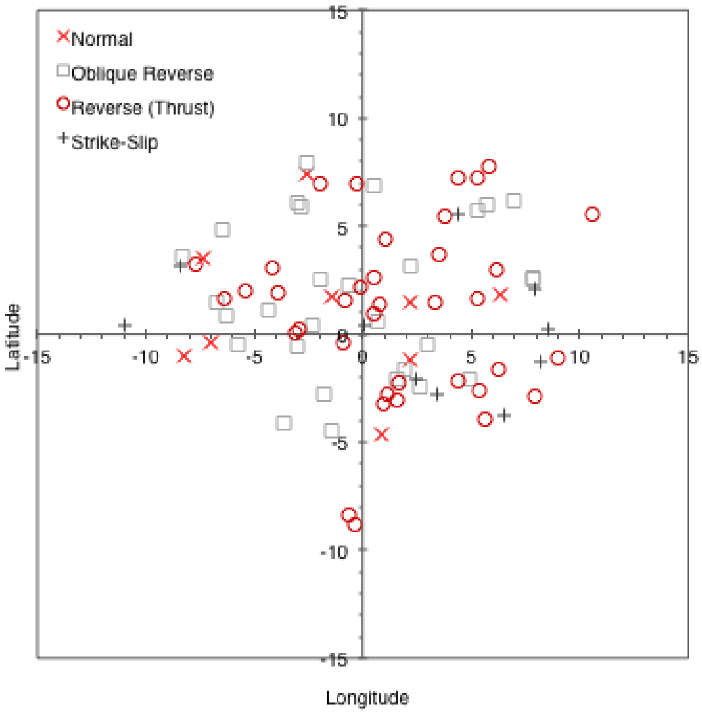


FIGURE 5-21 SPATIAL DISTRIBUTION OF TRIGGERED EARTHQUAKE-VOLCANO INTERACTIONS CLASSIFIED BY THE TYPE OF EARTHQUAKE FAULT.

5-5 SUMMARY

This chapter has presented and discussed the results of the regional assessment of the relationship between earthquakes and volcanic activity. On the basis of the criteria identified in Chapter 3, instances of triggered and non-triggered activity were identified along with their associated parameters that were examined as part of a statistical analysis to identify the significance of the relationship between earthquakes and volcanic activity and the parameters that influence it. Unlike the global assessment, the regional examination did not identify triggered earthquake-volcano interactions following earthquakes with M≥8.0. In fact, the largest earthquake identified to trigger thermal unrest was M7.4 (Indonesia, Event ID 61R). Therefore, on the basis of these varying interactions where at a global scale changes in volcanic radiant flux are identified following M≥8.0 earthquakes but an absence of triggered thermal responses at individual volcanoes following any M≥7.5 earthquake, it is evident that there are varying levels of control on the relationship between earthquakes and volcanoes. At a global scale, for example, a coupling may exist where large magnitude earthquakes are capable of initiating variations in volcanic activity and at a regional scale, a relationship exists where if the parameters surmised to influence triggering are met, an earthquake can initiate a new period of unrest or an increase in activity at volcanoes with on-going activity.

Earthquake-volcano response rates also suggest that the relationship between earthquakes and volcanic activity varies at different scales. The low overall response rate, for example, suggests that an earthquake only triggers a small proportion of volcanoes. Statistically significant instances of increased volcanic activity following an earthquake as well as those volcanoes that respond to more than one earthquake trigger or those earthquakes that trigger more than one volcanic response, however, demonstrate that these interactions are more than just a temporal coincidence. What is more, the varying levels of response at a global and regional scale as well as at individual volcanoes confirms the selectivity of volcanoes to triggering following an earthquake and supports the analysis of parameters conducted in this chapter.

In terms of a volcano's response, a volcano was identified to experience a period of increased volcanic radiant flux following an earthquake that was then followed by a return to pre-earthquake thermal activity. In both cases, the majority of responses occurred within 100 days of the triggering earthquake. While it is possible that longer temporal delays as observed in this thesis and previous research (e.g. Hill *et al*. 2002; Eggert and Walter 2009) are possible; volcanoes, particularly those with on-going activity, are more likely to exhibit triggered responses within 3 months of a seismic event. In addition, volcanoes with new activity following an earthquake trigger were identified to experience a longer period of increased volcanic activity.

Examinations of earthquake and volcano parameters then allowed the factors that influence the response of volcanoes to earthquakes to be assessed. Firstly, the majority of volcanoes were identified to be located in an area of compression following an earthquake. This suggests that those volcanoes that experience an increase in stress following an earthquake are most likely to be triggered. Alongside this, an earthquake's ability to initiate a response at more than one volcano demonstrates the importance of earthquake characteristics on the relationship between earthquakes and volcanic activity. This was further confirmed following statistical analyses that identified that earthquake fault characteristics are key in identifying a volcano's probability for response based on the parameters assessed in this research. However, responses at volcanoes with latent or on-going activity suggest that a volcano's readiness, or threshold, to erupt is also key in determining a response if all other conditions are met (Husen *et al*. 2004b; Moran *et al*. 2004; Brodsky and Prejean 2005).

The forthcoming chapter will now provide an evaluation of mechanisms that have been suggested to influence the relationship between earthquakes and volcanic activity on the basis of the results presented in this chapter as well as the global assessment of volcanic radiant flux responses to large magnitude earthquakes (Chapter 4). A process for response will also be proposed on the basis of the evidence presented to identify the factors that may control volcanic activity triggering following an earthquake.

CHAPTER 6

DISCUSSION

After identifying a standardised method and key criteria to ensure that only cases of potentially triggered earthquake-volcano interactions were identified (Chapter 3), this thesis examined the interactions between earthquakes and volcanic activity at a global and regional scale. On the basis of the factors identified to influence the relationship in Chapters 4 and 5, this chapter will provide an evaluation of proposed triggering mechanisms. Finally, the overall conditions that appear to control the potential for triggered activity will be proposed.

6-1 EVALUATION OF TRIGGERING MECHANISMS

On review of the findings of this research, the mechanisms suggested to control a volcano's response to earthquakes can be evaluated. Given the scale of previous studies, focusing on one set of interactions following an earthquake event (e.g. Dzierma and Wehrmann 2010) or within a specific region (e.g. Bebbington and Marzocchi 2011), for example, comparisons of different triggering mechanisms have not been conducted. This thesis will, therefore, assess the results of earthquake-volcano interactions in comparison to the mechanisms suggested to influence volcanic activity following earthquakes to identify the most likely mechanism(s) that control a response and identify uncertainties within the relationship between earthquakes and volcanoes.

Firstly, based on the presence of regional earthquake-volcano interactions at distances of more than 300 km as well as volcanic radiant flux responses at a global scale, it can be suggested that mechanisms related to dynamic stress change initiate processes of unrest (Delle Donne *et al*. 2010; Kato *et al*. 2013). During the passage of seismic waves, dynamic stress changes are shown to decay more slowly than static stresses (Hill *et al*. 2002; Manga and Brodsky 2006; Bebbington and Marzocchi 2011) and, therefore, have a much higher potential to influence volcanoes more than a few hundred kilometres from an earthquake's epicentre. This evidence corresponds with Eggert and Walter (2009) who state that due to the wide spatial effect of earthquakes initiating periods of volcanic unrest at a regional and global scale, processes related to dynamic stress are most likely. However, Watt *et al*.

(2009) suggested that if triggering following an earthquake was only related to changes in stress, earthquake magnitude would be expected to play a critical role. Similar increases in post-seismic eruption rates following the 1906 M8.3 and 1960 M9.5 Chile earthquakes as documented by Watt *et al*. (2009) and similar volcanic responses following earthquakes of different magnitudes in this research, however, do not support this and it is clear that the state of the volcanic system as well as other processes related to changes in stress also contribute to the probability of a volcano's response

In this regard, a volcano's location in an area of compression in 73% of cases and the identification of earthquake fault characteristics (Table 5-8, pg. 120) as controls over whether a response would be probable indicates that the size and direction of the fault may be more important than an earthquake's magnitude. As a result, triggering due to rupture directivity is the most likely mechanism initiating responses following an earthquake (Delle Donne *et al*. 2010). Further evidence to support triggering in zones of maximum stress change, as suggested by Husen *et al*. (2004a), Prejean *et al*. (2004) and Manga and Brodsky (2006), can be determined in cases of multiple response (where an earthquake triggers more than one response or where a volcano responds to more than one earthquake trigger). In all instances, Figure 5-20 (pg. 129) shows that triggering at the same volcano following an earthquake were located in a similar azimuth and distance to the responding volcano. Another critical indicator is the reduced accuracy of post-2012 predictions where 'Location of Volcano in Relation to Earthquake' was omitted. Sánchez and McNutt (2004), for example, previously stated that the concentration of wave energy along the azimuth of fault rupture plays a key role in the triggering mechanism. Therefore, responses in a particular direction as observed in this research and following previous earthquakes (e.g. Landers, California; Hector Mine, California and Denali Fault, Alaska) as well as those cases of non-triggered activity located within a different azimuth (Figure 5-2, pg. 100) suggest that strong dynamic stresses are the cause of the directivity effects identified (Anderson *et al*. 1994; Moran *et al*. 2004; Pollitz and Johnston 2006; Hill 2008; Delle Donne *et al*. 2010). Despite the evidence for triggering due to this mechanism, the lack of response at volcanoes in a similar azimuth but closer to the earthquake's epicentre following the 2002 Denali Fault event and the non-response of Pago, Papua New Guinea (Figure 5-2, pg. 100) suggests that rupture directivity alone may not account for the interactions observed (Moran *et al*. 2004).

Earthquake-induced decompression is another mechanism that is likely to play a critical role in triggering (Walter and Amelung 2007). This mechanism, in particular, provides evidence to support triggering at volcanoes with latent activity (especially those with long repose periods) as identified in the regional and global assessments (e.g. 10 new eruptions following 2004 M9.1 earthquake, Sumatra) of this thesis. In addition, although change in stress following an earthquake was not available for each earthquake-volcano interaction assessed, an examination of CMT focal mechanisms identified each responding volcano's location in an area of compression or dilatation. Increases in strain, in particular, initiate a process of volumetric expansion where the rock surrounding a volcanic centre is decompressed (Walter and Amelung 2007; Kriswati *et al*. 2013). This causes unclamping and magma ascent that could ultimately lead to an eruption (Walter and Amelung 2007). Importantly, modelling of this mechanism following four M≥9.0 earthquakes by Walter and Amelung (2007), Figure 6-1, has determined that triggering occurs in areas of permanent expansion. As a result, if dynamic stresses are the dominant force, a mechanism which transfers these stresses to permanent or static stress would also occur (Walter and Amelung 2007). This mechanism also supports the potential for decreases in activity following an earthquake, as observed in this research (Table 5-2, pg. 106). These responses are likely to be located in areas of increased stress where a volcano would be compressed and an eruption discouraged (Walter and Amelung 2007; Chesley *et al*. 2012). Importantly, modelling of this mechanism also indicated that an additional process such as rectified diffusion or advective overpressure is required to explain the overpressure that results in unrest following decompression (Walter and Amelung 2007). Therefore, it may be that a number of mechanisms contribute to the response of volcanoes following earthquakes.

FIGURE 6-1 MODELLING OF EARTHQUAKE-INDUCED DECOMPRESSION FOLLOWING FOUR M≥9.0 EARTHQUAKES. RED INDICATES AREAS OF VOLUMETRIC EXPANSION AND BLUE INDICATES VOLUMETRIC CONTRACTION (SOURCE: WALTER AND AMELUNG 2007: 541).

Viscoelastic relaxation is another similar mechanism that results from changes in stress on the surrounding rock, Figure 6-2 (Marzocchi 2002; Marzocchi *et al*. 2002; Bonali *et al*. 2012; Lupi *et al*. 2014). This mechanism provides evidence to support temporal delays of up to 362 days observed in both the global and regional assessments of this research (Manga and Brodsky 2006). Like earthquake-induced decompression, viscoelastic relaxation results in a relaxation of the earth's crust during and following an earthquake with an additional process required to initiate overpressure (Hill *et al*. 2002; Marzocchi 2002; Manga and Brodsky 2006; Bonali *et al*. 2012). Critically, this mechanism has been shown to account for triggering at large distances due to the slow spatial decay of quasi and dynamic stresses attributed to this process (Hill *et al*. 2002; Manga and Brodsky 2006; Bebbington and Marzocchi 2011). Therefore, triggering following temporal delays of more than 250 days and at distances of more than 250 km may be the result of viscoelastic relaxation at Anatahan, Mariana Islands; Chaiten, Chile and Redoubt, Alaska (Appendix IV).

FIGURE 6-2 STRESS DIFFUSION IN VOLCANIC AREAS FOLLOWING AN EARTHQUAKE. ARROWS REPRESENT VISCOELASTIC STRESS CHANGES, SCALE NOT PROVIDED (SOURCE: MARZOCCHI *ET AL*. 2002: 2).

While both earthquake-induced decompression and viscoelastic relaxation results in a change in stress that ultimately leads to overpressure and an eruption, an additional mechanism to initiate volatile excitation is needed. Rectified diffusion results from an increase in the mass of volatiles in a magma chamber, Figure 6-3, causing overpressure and leading to an eruption (Brodsky 2001; Manga and Brodsky 2006; Walter *et al*. 2007). Triggering by this mechanism suggests that a volcanic system must be saturated (i.e. in a critical state ready to erupt) prior to the event and an earthquake just causes a process of clock advance (Brodsky *et al*. 1998). Importantly, Lara *et al*. (2004) suggested that this mechanism has the ability to transfer dynamic stress to static stress as required in earthquake-induced decompression. However, the changes in stress related to this process are not large enough to cause triggering alone and other processes must work alongside this mechanism (Brodsky 2001; Ichiari and Brodsky 2006). Therefore, it is likely that there is an interplay of forcing mechanisms where earthquake-induced decompression or viscoelastic relaxation initiates a process of unrest and rectified diffusion causes an excitation of bubbles.

FIGURE 6-3 RECTIFIED DIFFUSION ASSOCIATED WITH THE PASSAGE OF SEISMIC WAVES THROUGH A MAGMA CHAMBER. A) A BUBBLE IN EQUILIBRIUM, B) EXPANSION FOLLOWING THE PASSAGE OF SEISMIC WAVES AND C) COMPRESSION. SHADING REPRESENTS VOLATILE CONCENTRATION (PRIMARILY WATER, CARBON DIOXIDE AND SULPHUR DIOXIDE) (SOURCE: BRODSKY 2001: 79).

In contrast, following the passage of seismic waves, advective overpressure has the potential to cause bubbles within the magma chamber to become dislodged and rise, resulting in an eruption or unrest (Linde *et al*. 1994; Watt *et al*. 2009). Once again, the strain changes associated with this mechanism are not sufficient to cause triggering directly and an additional process is required for a response to occur (Brodsky 2001). Earthquake-volcano interactions at Chaiten, Chile [Event ID - 48R] and Redoubt, Alaska [Event ID - 55R] provides evidence for triggering via viscoelastic relaxation and advective overpressure that resulted in delayed responses of 362 days and 302 days, respectively (Moran *et al*. 2004).

Further mechanisms that are not likely to act alone but may account for overpressure relating to earthquake-induced decompression or viscoelastic relaxation are a relaxing magma body, sinking crystal plume, hydraulic surge, magmatic overpressure and the creation of new bubbles (Johnston *et al*. 1995; Hill *et al*. 2002; Manga and Brodsky 2006; Eggert and Walter 2009). In all cases, the passage of seismic waves causes changes within the magma chamber that result in an eruption. While each of these mechanisms is supported by dynamic stress changes following the passage of seismic waves, there is no clear evidence that supports overpressure by one of these mechanisms in this research.

6-2 PROPOSED PROCESS OF RESPONSE

By considering the complex processes associated with each mechanism discussed in Section 6-1, it is clear that on the basis of the evidence presented in this research there is no single mechanism that can be proven to control the response of volcanoes to earthquakes. Most importantly, responses at a regional and global scale demonstrated that processes related to dynamic stress change are critical in influencing the response of volcanoes. However, varying response characteristics of triggered earthquake-volcano interactions suggest that the mechanisms discussed may act at different spatial and temporal scales. Multiple volcanic responses located in a similar azimuth to the triggering earthquake, for example, provide evidence to support triggering by rupture directivity whereas eruptions following periods of latent activity support triggering by earthquake-induced decompression and long temporal delays at Chaiten, Chile and Redoubt, Alaska indicate a process related to viscoelastic relaxation.

Alternatively, assessments of earthquake-volcano interactions and predictions using the machine learning model determined the parameters that are most likely to lead to a response. Figure 5-16 (pg. 123) presents an example of this for earthquake-volcano interactions in the Philippines. Similarly to Table 5-8 (pg. 120), this decision tree identified that earthquake rupture length and earthquake strike have the largest influence on determining if a response will occur. Therefore, it may be that globally a number of conditions or parameters need to be met for a response to be possible but at a regional scale, different forcing mechanisms may be triggered.

On the basis of these findings, when considering the potential for response, it may be possible that a hierarchy exists which is dependent on both the controlling parameters and triggering mechanisms (Figure 6-4). Firstly, on the basis of the selectivity of responses (i.e. not all volcanoes responded), it can be suggested that the parameters identified to influence whether a response occurs (rupture length, strike, magnitude, dip and depth) as well as spatial parameters (e.g. azimuth to responding volcano) increase the probability of volcanic activity triggering (Figure 6-4). At this stage, it is likely that rupture directivity plays a key role concentrating an earthquake’s wave energy along a certain path resulting in increased stress in areas aligned with the fault rupture and decreased stress in areas perpendicular to an earthquake's fault rupture (Figure 6-4). An interplay of secondary mechanisms (i.e. mechanisms resulting from changes in stress and mechanisms which lead to magma chamber overpressure) will then be triggered which will increase the probability of response (Figure 6-4). The state of the volcanic system (i.e. a volcano's readiness to erupt), in addition to the characteristics of the triggering earthquake, is then the most likely factor to determine whether a response will be observed (Figure 6-4). For example, some volcanoes with on-going activity may be more prone to triggering as demonstrated at Kliuchevskoi, Russia, or volcanoes with latent activity need to be in a critical state ready to erupt. This would result in a process of 'clock advance' where a volcano with magma present (i.e. ready to erupt) would be influenced by the changes in stress and the associated mechanisms resulting in premature activity.

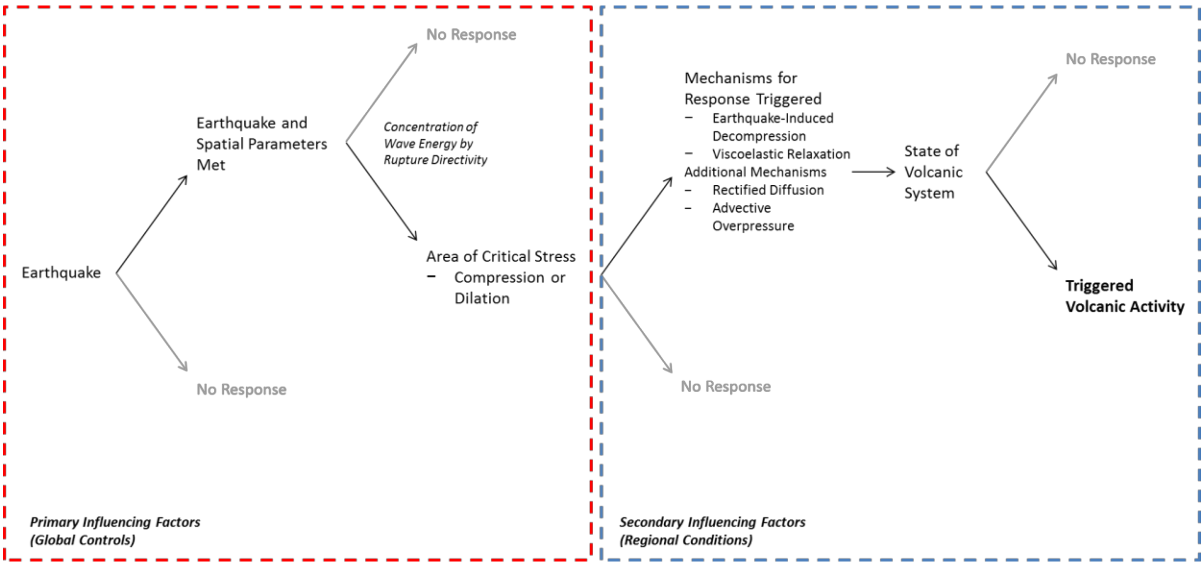


FIGURE 6-4 PROPOSED PROCESS OF RESPONSE BASED ON RESULTS PRESENTED IN THIS RESEARCH.

6-3 SUMMARY

This chapter has evaluated the most likely mechanism(s) that control a volcano's response to earthquakes based on the results presented in Chapters 4 and 5. Although the overall aim of Objective 6 to define the mechanism that controls a volcano's response has not been achieved, this chapter has proposed a process of response. In particular, by considering the evidence presented throughout this thesis it is clear that the relationship between earthquakes and volcanic activity is based on an interplay of factors with earthquake fault characteristics and the state of the volcanic system playing critical roles. Importantly, this research has identified a number of parameters that appear to be key in increasing the probability for a volcano to respond, a factor that has not been examined previously. The final chapter will now summarise the main implications of this thesis as well as providing an evaluation of this research and identifying opportunities for further work. Conclusions will also be drawn which outline the relationship between earthquakes and volcanoes and the mechanisms that contribute to a response.

CHAPTER 7

CONCLUSIONS

This thesis has used data from the MODIS sensor to examine the thermal response of volcanoes to earthquakes. Initial research to identify the factors that influence the relationship between earthquakes and volcanic activity as well as key challenges faced by previous research were identified in Chapter 2, satisfying Objective 1 of this thesis. Chapter 3 then set out a standardised method (Objective 2) to identify earthquake-volcano interactions as well as the associated earthquake and volcanic parameters. Critically, the identification of potentially triggered earthquake-volcano interactions indicated that the response of volcanoes following earthquakes is statistically different to similar periods where no change in volcanic radiant flux was detected.

Considering the varying spatial and temporal extents of the relationship identified in previous research, Objective 3 of this thesis aimed to assess the consistency of the relationship at varying spatial scales. The global study provided evidence to support both increased and decreased volcanic responses while the regional assessment identified that a number of parameters appear to be key in increasing a volcano's probability for response and at individual volcano's, this research identified that a volcano's readiness to erupt is critical in determining whether a response will occur. With regard to the parameters that influence any response (Objective 4), comparisons to non-triggered earthquake-volcano interactions and assessments of event parameters identified that earthquake fault characteristics have a large influence on a volcano's response. Variations between different regions, however, mean that there are still a number of uncertainties within the relationship and, as a result, it is suggested that any response is dependent of a hierarchy of processes related to the triggering earthquake and responding volcano.

Finally, Objectives 5 and 6 attempted to develop a model that predicts volcanic activity following earthquakes and determine the mechanisms that influence the relationship between earthquakes and volcanoes. While the overall aims of these objectives have not been achieved, this thesis has been able to reduce the number of uncertainties on the factors that influence a volcano's response. Chapter 5 also outlines the use of the Interaction model developed during machine learning analyses to predict the probability of a response following an earthquake. Although simulations using this model did not report 100% prediction accuracies, it did demonstrate the potential use of earthquakes as a precursory indicator to volcanic activity. Alongside this, a process for response was proposed that identified the most likely processes and mechanisms that lead to seismically triggered volcanic activity.

7-1 ASSESSMENTS OF EARTHQUAKE-VOLCANO INTERACTIONS

With reference to previous literature, this thesis identified a need to outline a standardised method to determine potentially triggered earthquake-volcano interactions. Discrepancies between previous studies based on varying spatial and temporal assessments have meant that comparisons between different sub-regions or volcanoes were not possible. Therefore, a set of response criteria as well as an appropriate temporal window were determined that was used in this research and can be applied to future assessments of earthquake-volcano interactions. Alongside this, this research employed the use of thermal remote sensing to provide globally comparable retrievals of volcanic radiant flux. While thermal anomalies are not indicative of all types of unrest, thermal hotspots have been recognised as a reliable indicator to- and precursor of- eruptive activity (e.g. Webley *et al*. 2008; van Manen *et al*. 2013) and is, therefore, used as a proxy for volcanic activity in this thesis. Future assessments, however, could replicate these methods by substituting the use of thermal activity data with measurements of volcanic deformation or seismicity to provide a comprehensive assessment of volcanic activity responses to earthquakes.

Within the assessment of earthquake-volcano interactions, the inter-annual variability in volcanic radiant flux ($v + 1\sigma$) and the β-statistic were employed to identify significant changes in volcanic activity following earthquakes. The inter-annual variability in volcanic radiant flux ($v + 1\sigma$) developed in this thesis gives an indication of volcanic radiative energy as compared to normal or 'baseline' volcanic behaviour. The examination of such time series data can, therefore, be updated and extended enabling a wider application to volcanic activity monitoring allowing changes in behaviour to be identified in near real-time, aiding hazard warning. The β-statistic previously implemented by Walter and Amelung (2007) was also adopted in this research to identify the significance of the triggering observed. Importantly, the use of the β-statistic has demonstrated the benefit of examining different indicators to volcanic unrest as well as identifying the significance of triggered activity that supports a relationship between earthquakes and volcanic activity.

For example, the use of the β-statistic alongside $v + 1\sigma$ has shown that, in some cases, the overall change in volcanic radiant flux remained constant while the change in the number of erupting volcanoes (β-statistic) had increased or vice versa. This demonstrates the advantage of using multiple measures for response to reliably identify new activity following triggering or increases in activity at volcanoes with on-going activity.

Prior to this research, few studies had considered the strength of the relationship at varying spatial scales. This research, therefore, focussed on examining interactions at a global, regional and local scale. The specific utility of this approach enabled the global volcanic radiant flux following large magnitude earthquakes to be assessed as well as the identification of globally comparable earthquake-volcano interactions. The strength of the earthquake-volcano relationship (i.e. response rate) at each scale of study also enabled a better understanding of the variability of the relationship as well as the inconsistency of the relationship within different regions and at individual volcanoes. Rather than examining individuals regions or volcanoes to suggest triggering mechanisms that have resulted in a failure to understand the relationship as a whole, this research considered the parameters that were suggested to contribute to the relationship or play a key role in triggering. This allowed a more comprehensive examination of factors that increase a volcano's probability for response. Comparisons to non-triggered earthquake-volcano interactions and examinations using machine learning models revealed that the relationship between earthquakes and volcanoes is not universal and is, in fact, due to an interplay of different factors that contribute to a volcano's response following triggering.

Finally, this research assessed the predictive utility of earthquakes as precursory indicator to volcanic activity. Although this is not the first study to use precursors or triggers to predict volcanic activity, it is the first to attempt to provide predictions on a volcano's response following earthquakes. It is also the first to incorporate earthquake and volcano parameters as measures for likelihood of response. While the model developed in this thesis cannot be applied in routine volcanic activity forecasting, it does demonstrate the potential use of earthquakes a precursory indicator to volcanic activity.

7-2 SIGNIFICANCE OF FINDINGS

This research has identified interactions between earthquakes and volcanic activity at 3 spatial scales. Within a global setting, increases and decreases in global volcanic radiant flux were identified following M≥8.0 earthquakes. The most significant change in volcanic activity followed the 2004 M9.1 Sumatra earthquake where $v + 1\sigma$ was exceeded for up to 3 months, conversely the 2011 M9.0 Japan earthquake did not elicit similar responses. At a regional scale, this research showed that cases of triggered activity were statistically different to non-triggered instances as well as determining the role of earthquake and volcano parameters. Finally, it was identified that a volcano's readiness to erupt is critical. For example, some volcanoes experienced multiple responses following earthquakes whereas volcanoes with latent activity prior to an earthquake only responded once in the majority of cases.

Within a regional environment, this research compared instances of triggered activity to instances where no triggering was observed. Comparisons to non-triggered earthquake-volcano interactions, in particular, have not been examined previously. On the basis of these analyses, this research enabled the difference in the characteristics of triggered and non-triggered activity to be determined identifying earthquake fault characteristics as well as a volcano's location to the triggering earthquake (i.e. azimuth and location in an area of compression or dilatation) to be critical in influencing a volcano's response. Different response proportions of individual volcanoes, however, demonstrate that the role of the volcanic system (i.e. its readiness to erupt) is also important in determining whether a response will be triggered. Therefore, although parameters related to the earthquake may increase the probability of triggered activity, whether a response is observed is dependent on the individual volcano.

At a global, regional and local scale, this thesis also provided evidence to suggest that a number of mechanisms act to initiate unrest. Multiple volcanic responses located within the same azimuth to the triggering earthquake and the same spatial location of earthquakes at volcanoes with multiple responses provides evidence to support the role of rupture directivity in volcanic activity triggering. As a result, on the basis of this research, it can be suggested that rupture directivity is a primary mechanism initiating changes in stress following an earthquake and increasing a volcano's potential for response. Secondary mechanisms may then act to initiate processes of unrest and magmatic overpressure. Volcanoes located in areas of increased strain, for example, support triggering by earthquake-induced decompression while long temporal delays between the triggering earthquake and responding volcano indicate triggering by viscoelastic relaxation. In this regard, it is proposed that the relationship between earthquakes and volcanoes is based on a hierarchy of factors. Firstly, for a response to be possible the parameters (primary factors) identified to increase a volcano's potential for response need to be met and an earthquake's wave energy needs to be concentrated along a certain path (i.e. rupture directivity). Secondary factors that are likely to influence individual volcanoes are a volcano's readiness to erupt and the mechanism(s) that lead to seismically triggered unrest. However, based on the evidence in this research, it is unclear what factors determine the mechanism(s) that lead to triggering.

Finally, modelling of earthquake-volcano interactions in this research confirmed the potential use of earthquakes as precursors to volcanic activity. While assessments in this research did not identify any distinct relationships between different regions, it did recognise variations in the relationship based on different subsets of data. In addition, based on the parameters assessed in this research, the model predicted the correct response in 75% of cases. As such, while the results of this research are not useful as a predictor of a response at individual volcanoes, this model could be used in future assessments to provide a scenario-based prediction of the likeliness of regional earthquake-volcano interactions. In this way, the model could indicate a probability for response following earthquakes as well as accounting for uncertainties identified by previous research.

Overall, this thesis has important implications in determining any relationship between earthquakes and volcanoes. Firstly, the use of response criteria has shown that periods of change following earthquakes are significant and, therefore, confirmed the existence of earthquake-volcano interactions. Despite this, the small number of responses identified in this thesis means that, as yet, the use of any relationship is not statistically useful for the prediction of volcanic activity following earthquakes. Alongside this, comparisons of triggered and non-triggered activity have demonstrated that a number of conditions need to be met for a response to be possible. These findings, in particular, informed the development of a volcanic forecast model and predictions of earthquake-volcano interactions demonstrated the importance for research to identify precursors to natural hazards. Finally, this thesis confirmed the potential to use earthquakes as a precursory indicator to volcanic activity. These findings have the potential to aid hazard understanding and volcanic activity forecasting by identifying the factors that increase a volcano's potential for response as well as disaster management by providing scenario-based predictions of future interactions that could be incorporated into regional assessments of risk and disaster management plans.

7-3 EVALUATION

Overall, this research has successfully identified a number of earthquake-volcano interactions as well as the parameters that contribute to triggering. Despite this, there are a number of considerations that could impact the results observed. The use of the MODVOLC algorithm, in particular, enabled a proxy for volcanic activity to be determined and, as discussed in Section 6-2 (pg. 139), there may be other mechanisms that control seismic or deformation responses. Therefore, while the processes of response proposed in this research are indicative of thermal responses to earthquakes, it may not be reflective of the relationship as a whole. This is particularly applicable to the 2010 M8.8 Chile earthquake. While this research identified a decrease in thermal activity at a global scale and no regional responses, research by Pritchard *et al*. (2013) did identify subsidence at volcanic centres following this event. Future assessments of the thermal and physical response of volcanoes using the recommended method in this thesis could, therefore, identify additional earthquake-volcano interactions. Until the recent launch of the Sentinel-1 satellite (Torres *et al*. 2012; Aschbacher *et al*. 2014), however, globally continuous data to measure deformational changes has not been available.

The high detection threshold of the MODVOLC algorithm (Wright *et al*. 2002) may have also impacted on the number of responses identified. Considering the response criteria for changes in volcanic radiant flux of ±100% to identify potentially triggered activity, the use of the MODVOLC algorithm is appropriate for this study. In addition, it is recognised that satellite retrievals of volcanic radiant flux are not 100% accurate (e.g. Steffke and Harris 2011). Future studies that replicate these methods at a regional or local scale should, therefore, use an alternative or modified MODVOLC algorithm that would provide an improved estimate of volcanic radiant flux. The spatial resolution of the MODIS sensor, the presence of clouds and the bow-tie effect (discussed in Section 2-5-1, pg. 50) may have also resulted in over- or under- estimations in detected volcanic radiant flux due to missed detections, double counting or false alarms. As a result, measures (i.e. use of MODIS LST product and removal of duplicate pixels based MODVOLC-derived UNIX Time ID) to combat these issues as well as response criteria were employed in this thesis.

The need for a reliable methodology to mitigate the limitations of previous research in identifying any relationship also meant that the criteria employed might not identify all cases of triggering. In particular, only significant changes in activity, i.e. changes in radiant flux of more than 100%, are regarded as triggered. Therefore, small variations in activity resulting from an earthquake trigger are not analysed. Equally, the minimum number of 5 radiant flux detections to identify a significant change in activity means that eruptions of less than a few days, such as that at Mount Ontake, Japan in September 2014 (Smithsonian Global Volcanism Program 2015), would not be classed as triggered. While it is equally likely that these events are the result of triggering, the need for strict criteria to limit the identification of temporally coincident volcanic activity means that these instances were not considered. To incorporate these types of response, further research is required to identify the characteristics and, therefore, response criteria of these triggered responses. As a result, it may be that the 47 volcanoes that were identified as non-triggered in this research do have cases of potentially triggered activity. In addition, following the identification of only 2 cases of decreased activity it is clear that a modified method needs to be developed to reliably identify decreases in activity. In particular, further research is required to determine appropriate temporal delays and changes in volcanic flux related to decreased activity.

Finally, Chapter 2 discussed the effect that multiple seismic events may have on triggering. After identifying the need to assess the parameters related to an earthquake trigger and responding volcano, however, the effect of cumulative seismic energy was not considered at a regional scale. In future investigations, examinations of cumulative stress changes using ground-based or InSAR measurements could examine the effect of multiple seismic events on encouraging volcanic unrest. Similarly, stress changes around a volcanic centre following an earthquake were not examined. While an estimate of compression or dilatation (based on the CMT focal mechanism) provided key information on the zone of triggered activity, more reliable estimations of stress change at volcanic centres may be more indicative of the forcing mechanisms or identify volcanoes that are temporal coincidences rather than potentially triggered.

7-4 RECOMMENDATIONS FOR FURTHER RESEARCH

Following a review of previous earthquake-volcano interactions research, it was clear that a standardised method was required in order for comparisons between different studies to be made. In conducting future assessments of the relationship, therefore, it is recommended that the response criteria set out in this thesis are employed to identify potentially triggered activity. This would allow comparisons to different regions as well as scales of study or different types of response to be made allowing the variability in earthquake-volcano interactions to be determined as well as the factors that cause it. Further to this, this thesis presented statistically significant instances of increased volcanic activity following earthquakes as well as identifying the parameters that influence a volcano's response. A number of uncertainties related to the mechanisms that lead to seismically triggered unrest and the selectivity of responses, however, mean that the overall relationship between earthquakes and volcanoes was not determined. To be able to understand the role of each parameter and mechanism it is recommended that further investigations of earthquake-volcano interactions should focus on assessing individual volcanoes where in-depth information on the magmatic system is available. This will enable all possible responses to be identified and the effect of each mechansism on the dynamics of the volcanic system to be measured. Alternatively, the time-series for analysis could be extended to include data from sensors such as AVHRR or Landsat that have been collecting data since the 1970's as well as utilising data from recently launched sensors such as the Sentinel series. In essence, this would allow more earthquake-volcano interactions to be examined and, as a result, a deeper understanding of the factors that lead to seismically triggered unrest to be determined.

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APPENDIX I

SOURCES OF PARAMETERS EXAMINED IN THE REGIONAL ASSESSMENT OF EARTHQUAKE-VOLCANO INTERACTIONS

Parameter	Source
Earthquake Date	United States Geological Survey, National Earthquake Information Centre
Earthquake Latitude & Longitude	United States Geological Survey, National Earthquake Information Centre
Volcano	All volcanoes with MODVOLC detected thermal activity and meeting the criteria for response
Date of Volcanic Response	Identified using MODVOLC Data
Volcano Latitude & Longitude	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Change in Radiant Flux (%)	Calculated from MODVOLC data
β-Statistic	Calculated using equation -
Earthquake Magnitude	United States Geological Survey, National Earthquake Information Centre
Earthquake Rupture Length (km)	Estimated using rupture length formula in Wells and Coppersmith (1994) -
Earthquake Depth (km)	United States Geological Survey, National Earthquake Information Centre
Earthquake Azimuth to Volcano (°)	Identified using earthquake and volcano locations, azimuth measured from the earthquake to the volcano
Earthquake Strike (°)	Global Centroid Moment Tensor (CMT) Project Catalog (http://www.globalcmt.org/CMTsearch.html)
Earthquake Dip (°)	Global Centroid Moment Tensor (CMT) Project Catalog (http://www.globalcmt.org/CMTsearch.html)
Type of Earthquake Fault	Global Centroid Moment Tensor (CMT) Project Catalog (http://www.globalcmt.org/CMTsearch.html)
Incoming Earthquake Wave Direction	Based on geographic location (compass bearings) between earthquake and volcano
Region of Earthquake	ESRI Canada 2012
Tectonic Setting of Earthquake's Location	ESRI Canada 2012
Tectonic Plate of Earthquake's Location	ESRI Canada 2012
Type of Volcanic Response	Identified using MODVOLC detected thermal hotspots and the Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
VEI of Volcanic Activity	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)

Length of Volcanic Response (Days)	Calculated from MODVOLC data
Time Since Last Period of Volcanic Activity (Years)	Calculated from date of last eruption using MODVOLC and Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Status of Volcano at Time of Earthquake	Identified using MODVOLC and Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Volcano Type	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Magma Composition	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Surrounding Volcanic Geology	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Region of Volcano	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Tectonic Setting of Volcano's Location	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Tectonic Plate of Volcano's Location	ESRI Canada 2012
Type of Crust of Volcano's Location	Smithsonian Global Volcanism Program (http://www.volcano.si.edu)
Temporal Delay Between Triggering Earthquake and Responding Volcano (Days)	Calculated from MODVOLC data
Distance (km)	Identified using earthquake and volcano locations
Location of Volcano in Relation to Earthquake	Based on geographic location (compass bearings) between earthquake and volcano
Volcanic Compression or Dilatation	Global Centroid Moment Tensor (CMT) Project Catalog (http://www.globalcmt.org/CMTsearch.html)

APPENDIX II

VOLCANIC RADIANT FLUX PER VOLCANO

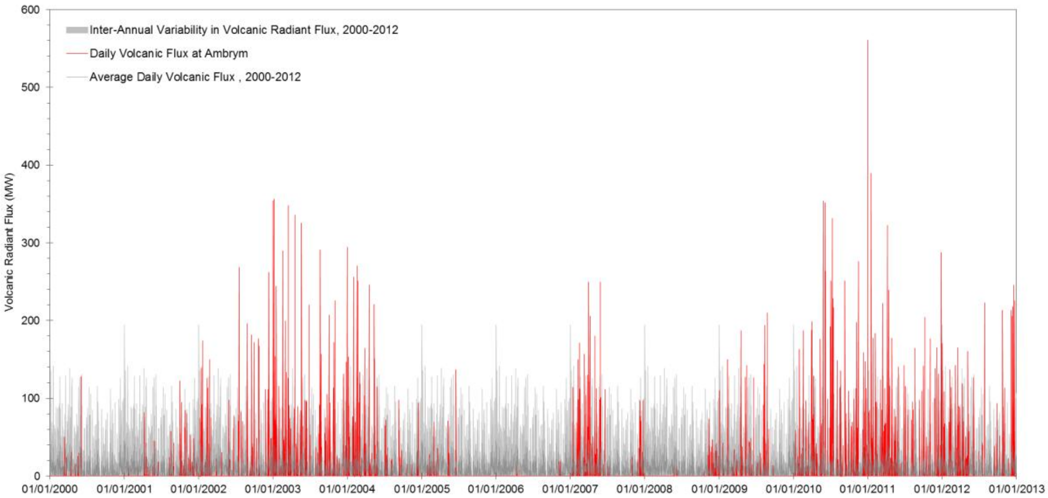
Volcano	Total Flux Per Volcano (MW)	% of Total Flux
Alaid	1,748.83	0.03
Ambrym	43,277.55	0.63
Anatahan	10,713.49	0.16
Arenal	1,710.35	0.02
Asamayama	334.98	0.005
Augustine	13,153.30	0.19
Awu	128.30	0.002
Bagana	29,579.97	0.43
Barren Island	64,967.05	0.94
Batu Tara	48,445.42	0.70
Bezymianny	11,700.02	0.17
Cameroon	12,752.66	0.18
Cerro Azul	15,397.36	0.22
Chaiten	29,900.96	0.43
Chirpoi	919.94	0.01
Cleveland	970.79	0.01
Colima	8,937.86	0.13
Copahue	447.28	0.01
Dalaffilla	11,169.01	0.16
Dukono	1,411.69	0.02
Erebus	226,928.85	3.29
Erta Ale	71,011.19	1.03
Etna	741,860.13	10.75
Eyjafjallajökull	51,450.04	0.75
Fernandina	114,127.26	1.65
Fuego	62,969.84	0.91
Galeras	156.46	0.002
Gaua	57.63	0.001
Gorely	173.34	0.003
Heard	7,162.68	0.10
Hekla	3,661.59	0.05
Ibu	2,931.55	0.04
Ijen	901.22	0.01
Jebel at Tair	79,742.21	1.16
Karangetang	14,316.74	0.21
Karthala	18,145.96	0.26

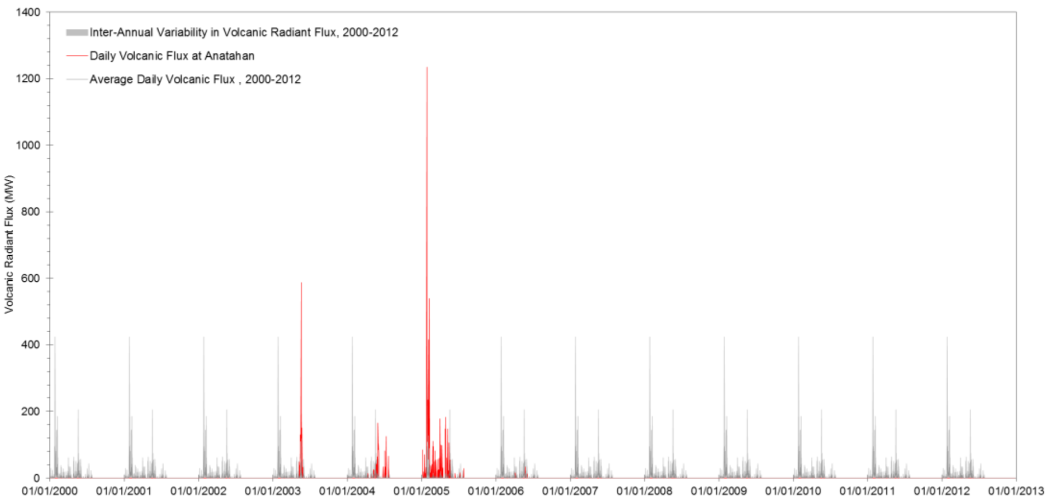
Karymsky	21,337.42	0.31
Kavachi	125.80	0.002
Kelut	894.79	0.01
Kerinci	542.17	0.01
Kilauea	1,547,823.43	22.43
Kirishima	3,913.37	0.06
Kizimen	55,173.42	0.80
Kliuchevskoi	457,797.79	6.63
Krakatau	8,225.80	0.12
Langila	2,269.00	0.03
Lascar	1,195.22	0.02
Llaima	29,797.36	0.43
Lopevi	28,018.89	0.41
Manam	33,487.89	0.49
Manda Hararo	26,219.89	0.38
Mayon	16,092.72	0.23
Merapi	9,325.32	0.14
Michael	1,769.13	0.03
Mount Belinda	13,977.19	0.20
Mount St. Helens	3,745.84	0.05
Nabro	58,392.46	0.85
Nevado del Huila	1,126.67	0.02
Nyamuragira	681,194.61	9.87
Nyiragongo	1,014,443.99	14.70
Ol Doinyo Lengai	4,313.58	0.06
Pacaya	45,152.56	0.65
Pagan	83.11	0.001
Pago	6,465.04	0.09
Paluweh	2,511.98	0.04
Pavlof	7,905.50	0.11
Piton De La Fournaise	267,132.71	3.87
Popocatépetl	31,282.75	0.45
Puyehue-Cordón Caulle	24,346.84	0.35
Rabaul	8,572.55	0.12
Raung	949.39	0.01
Redoubt	1,225.84	0.02
Reventador	11,589.26	0.17
Rinjani	13,915.00	0.20
Ruang	192.36	0.003
Sakura Jima	1,354.58	0.02
San Miguel	132.41	0.002
Sangay	3,404.37	0.05
Santa Ana	138.81	0.002
Santa Maria	23,341.84	0.34

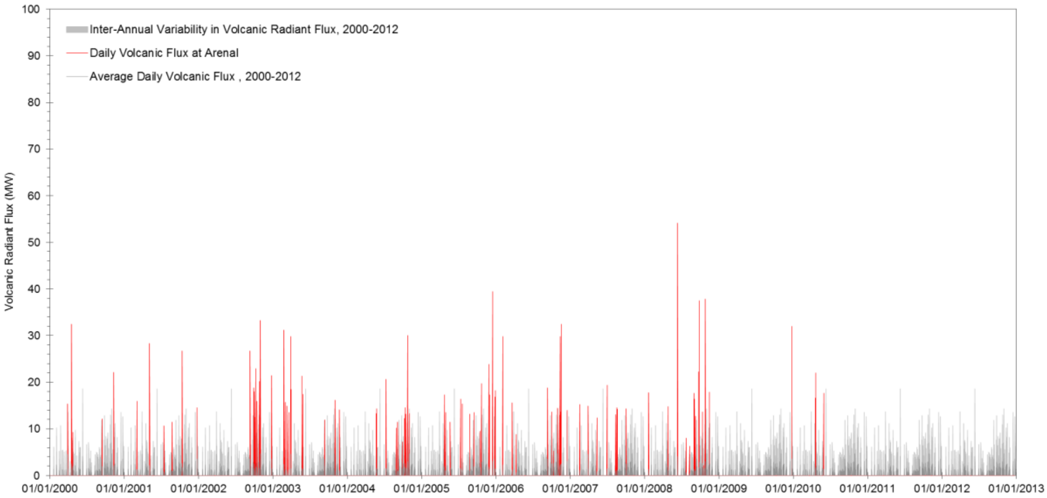
Sarychev Peak	11,128.23	0.16
Semeru	44,846.87	0.65
Shishaldin	82.19	0.001
Shiveluch	177,660.14	2.57
Sierra Negra	55,551.79	0.80
Slamet	1,112.33	0.02
Soputan	13,625.20	0.20
Soufrière Hills	73,758.05	1.07
Stromboli	40,734.84	0.59
Suwanose Jima	476.58	0.01
Tinakula	11,931.27	0.17
Tofua	739.99	0.01
Tolbachik	243,428.14	3.53
Tungurahua	12,256.97	0.18
Ubinas	343.98	0.005
Ulawun	1,530.13	0.02
Veniaminof	143.89	0.002
Villarrica	14,238.73	0.21
Yasur	23,313.58	0.34

APPENDIX III

INTER-ANNUAL VARIABILITY ($V + 1\sigma$) IN VOLCANIC RADIANT FLUX FOR ALL VOLCANOES WITH EARTHQUAKE-VOLCANO INTERACTIONS






Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Arenal
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
100
90
80
70
60
50
40
30
20
10
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
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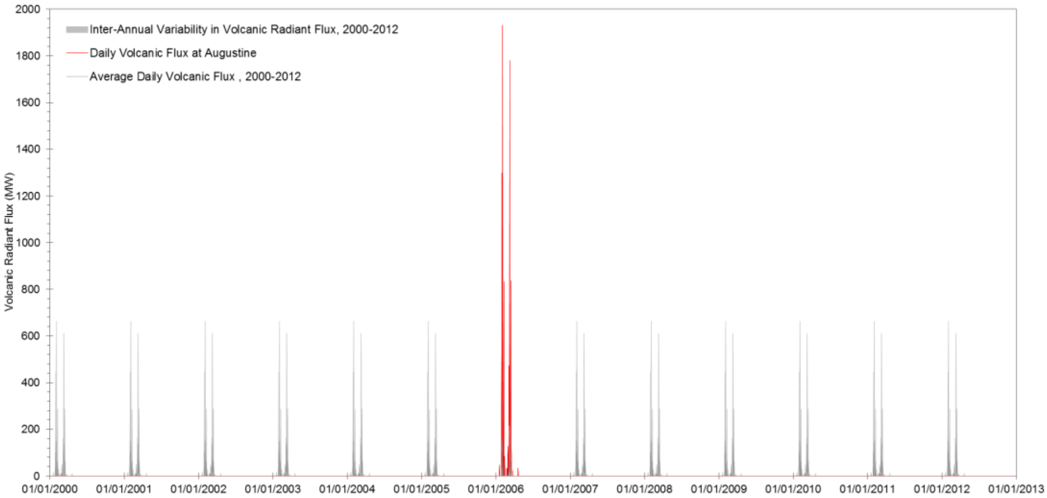
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Augustine
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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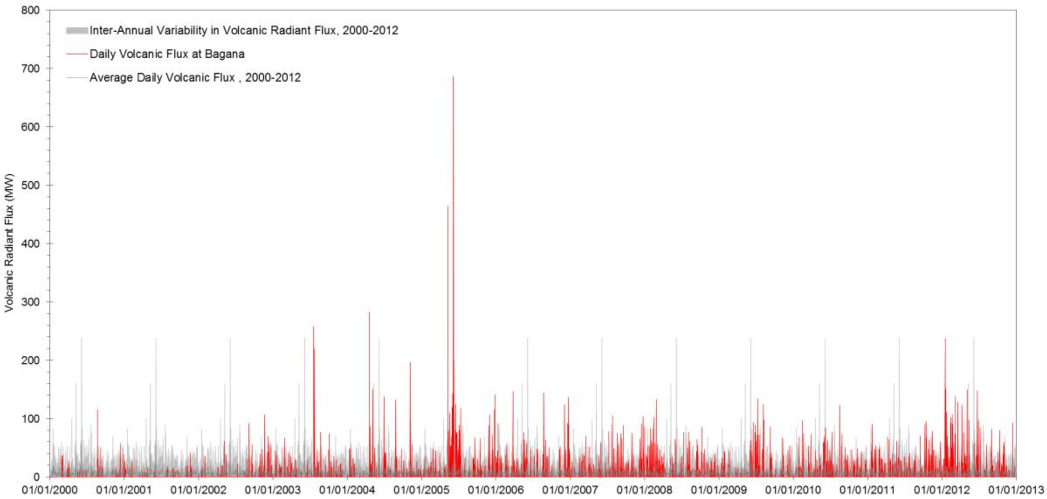
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Bagana
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
800
700
600
500
400
300
200
100
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
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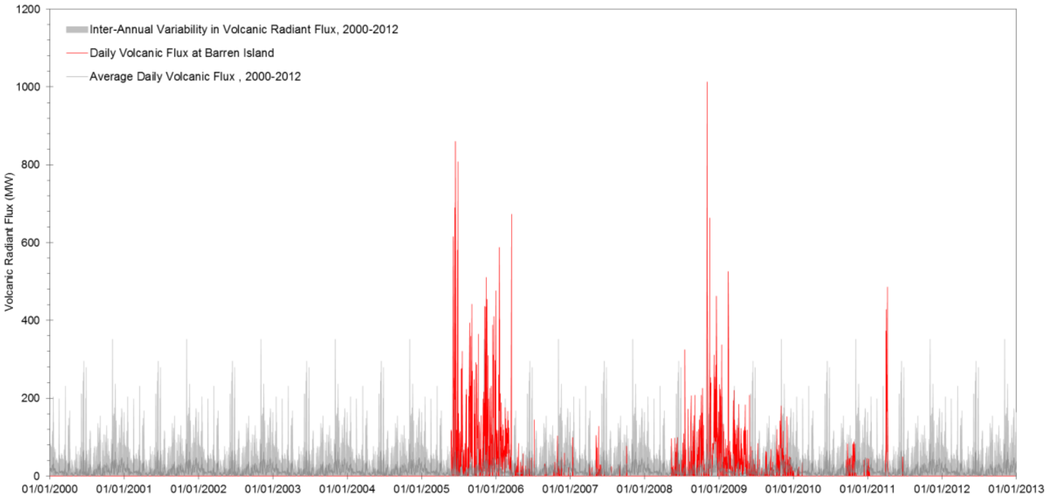
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Barren Island
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
200
400
600
800
1000
1200
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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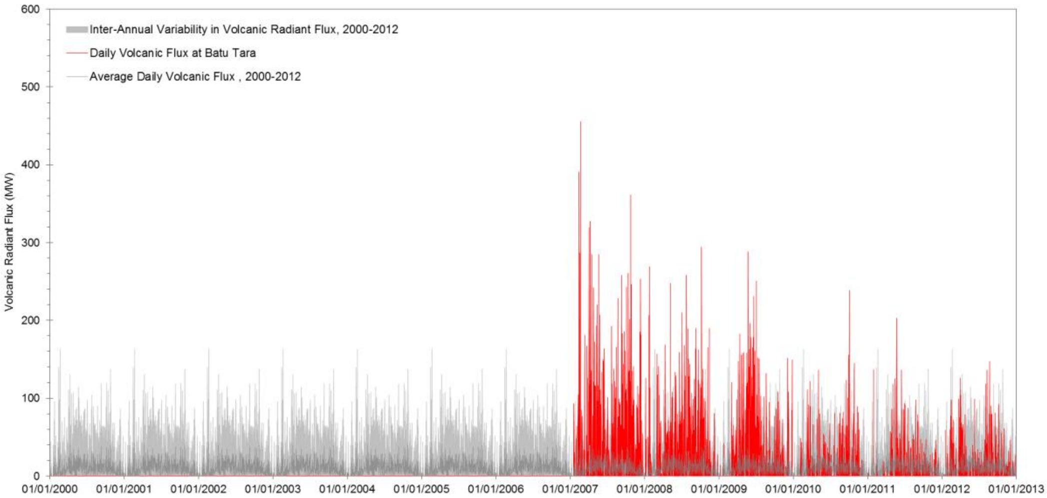
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Batu Tara
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
100
200
300
400
500
600
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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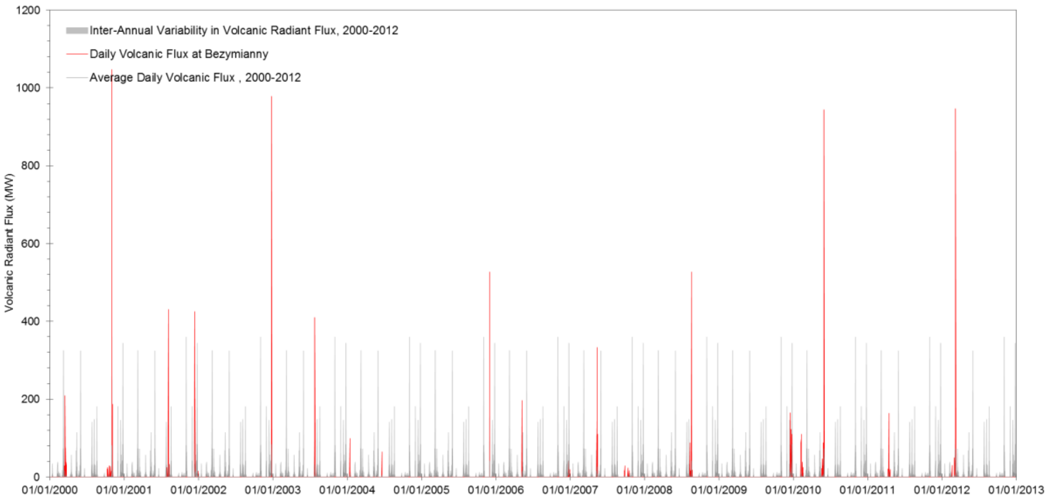
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Bezymianny
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
200
400
600
800
1000
1200
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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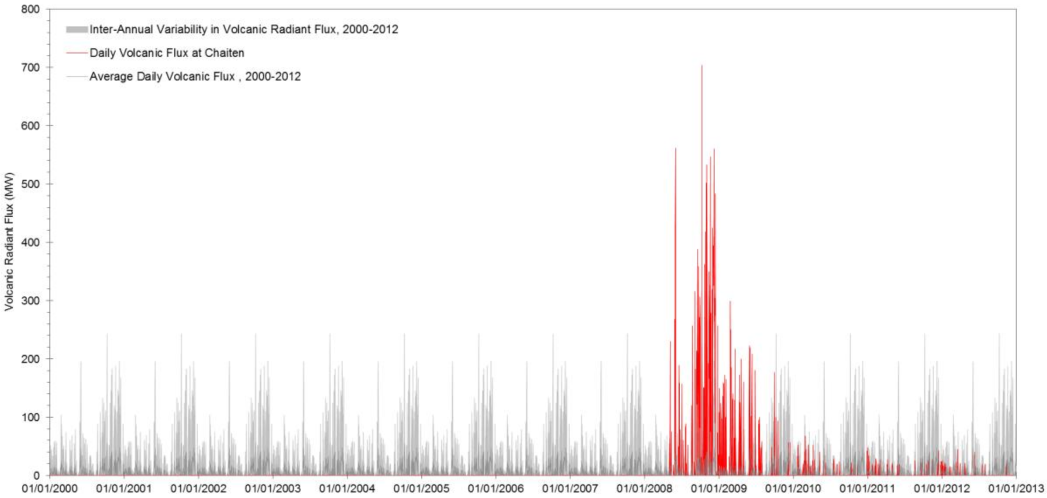
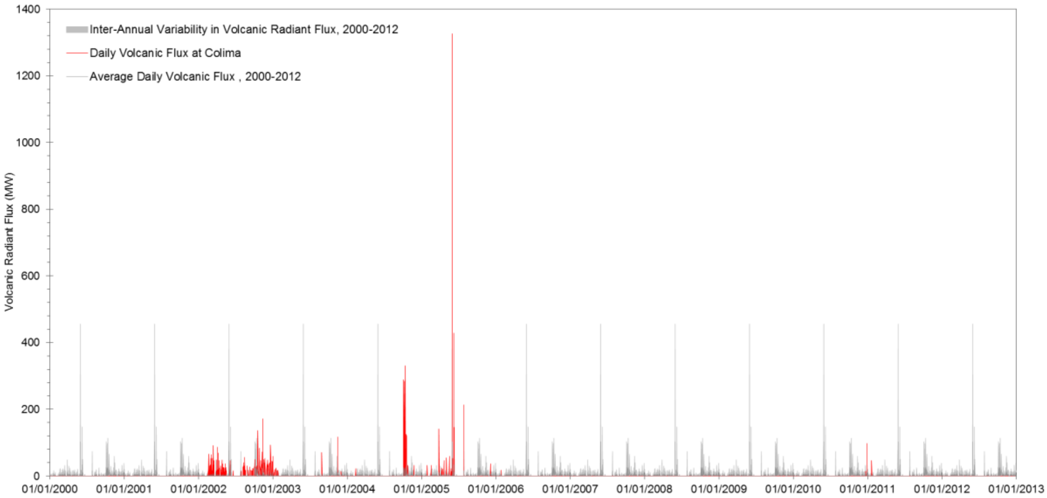
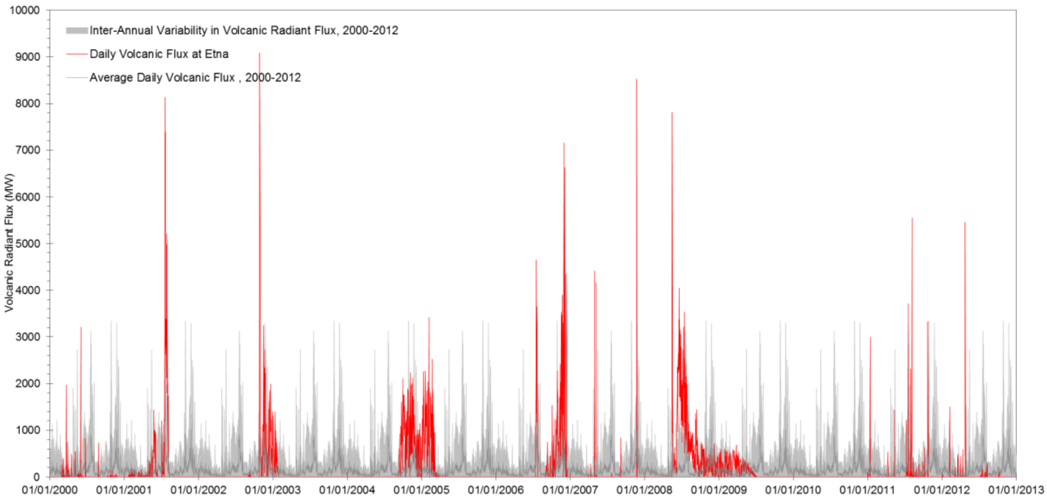
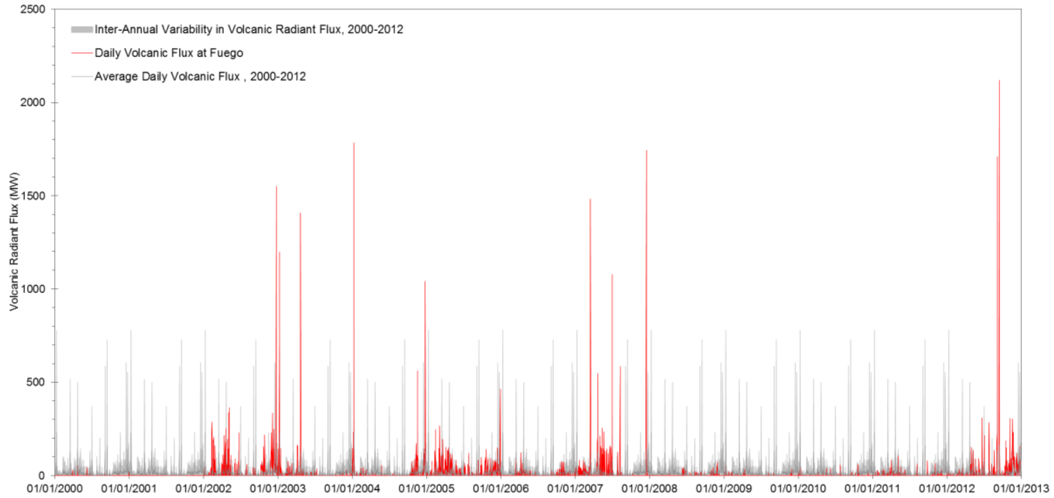
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Chaiten
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
100
200
300
400
500
600
700
800
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Colima
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
200
400
600
800
1000
1200
1400
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Etna
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Fuego
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
2500
2000
1500
1000
500
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
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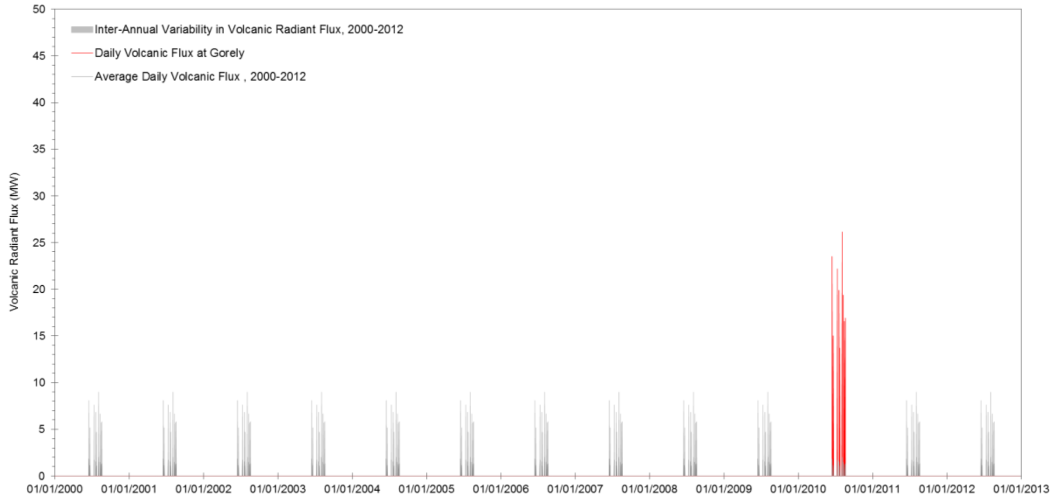
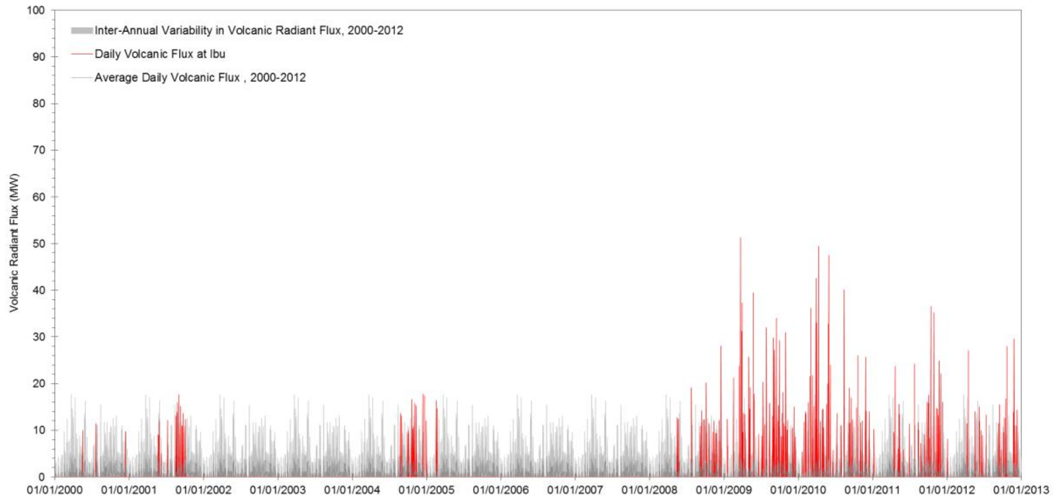
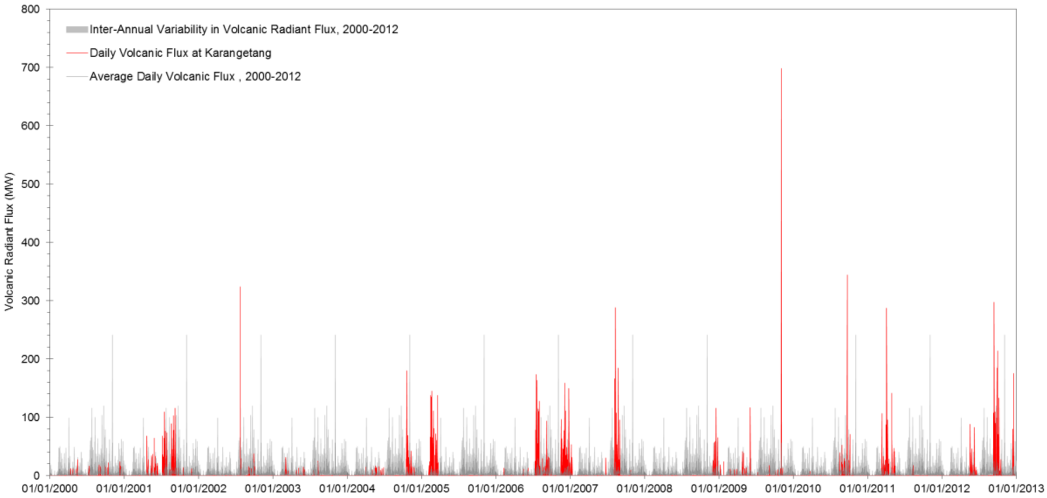
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Gorely
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
50
45
40
35
30
25
20
15
10
5
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Ibu
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
100
90
80
70
60
50
40
30
20
10
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Karangetang
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
100
200
300
400
500
600
700
800
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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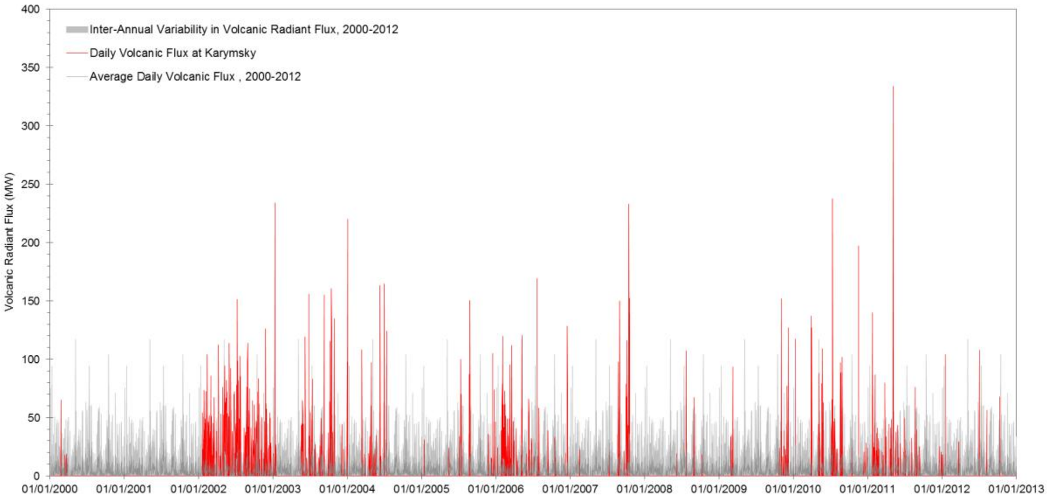
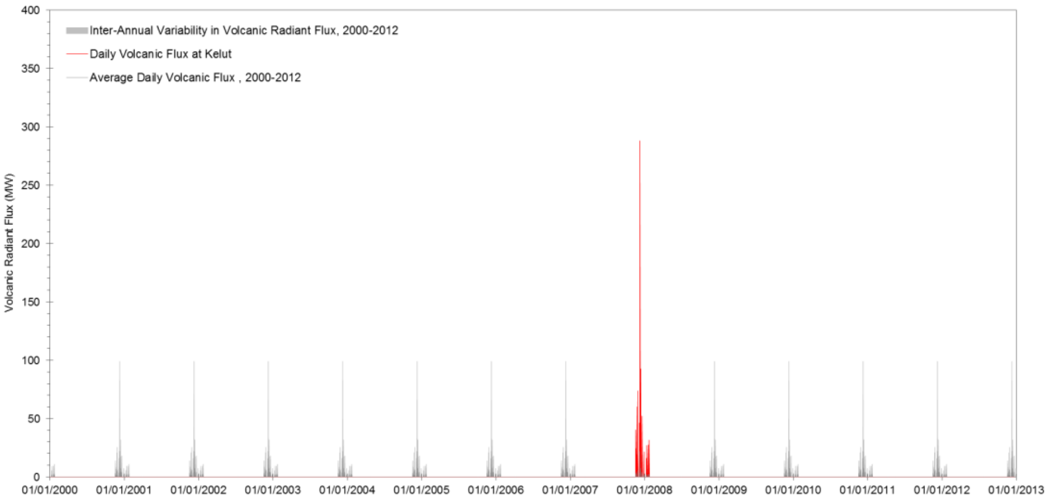
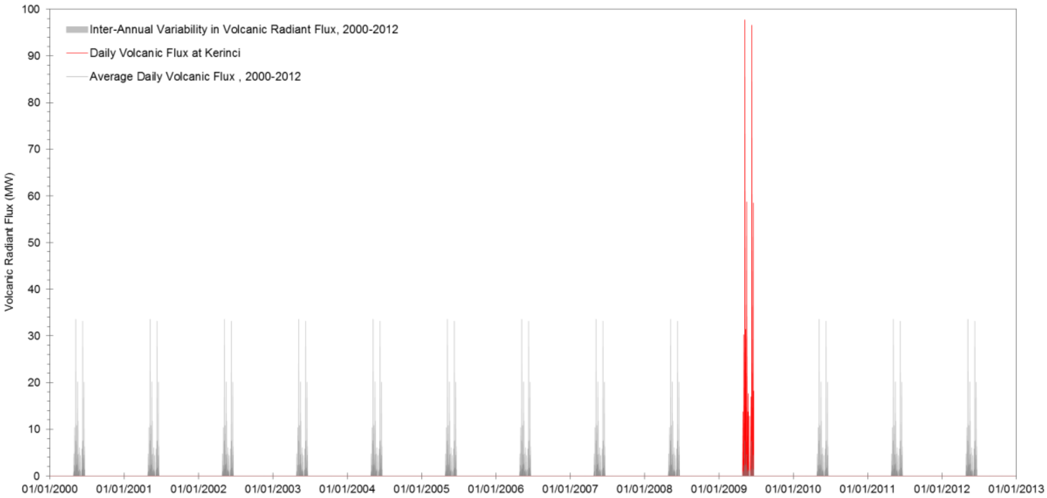
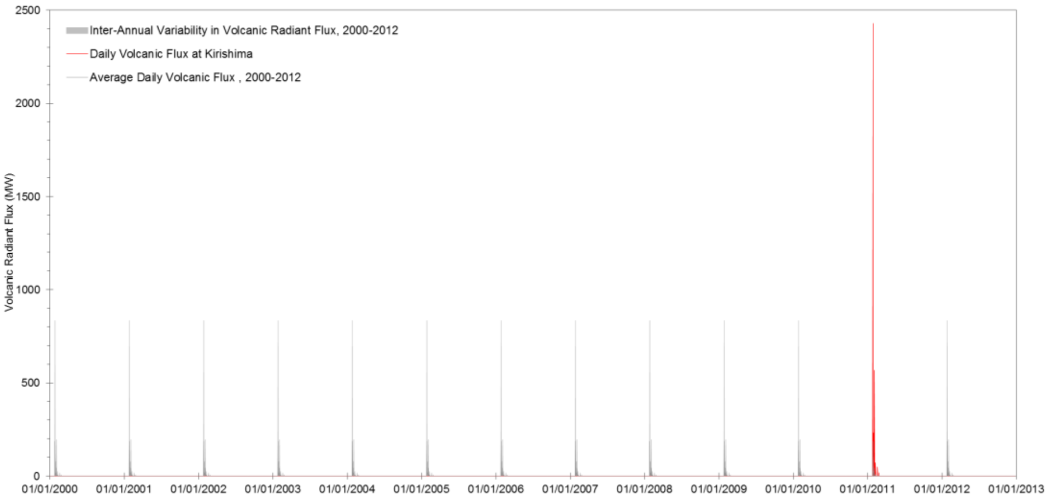
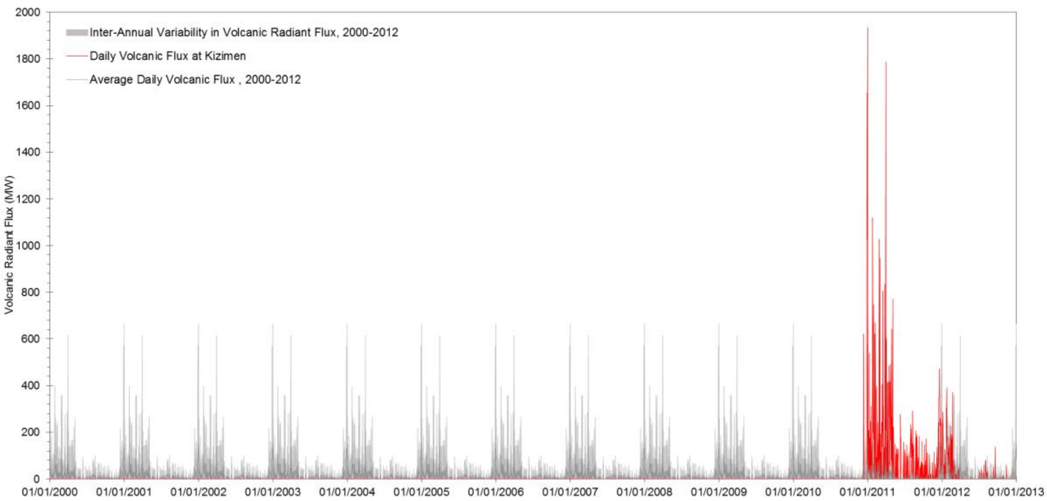
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Karymsky
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
350
400
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Kelut
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
350
400
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Kerinci
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Kirishima
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Kizimen
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
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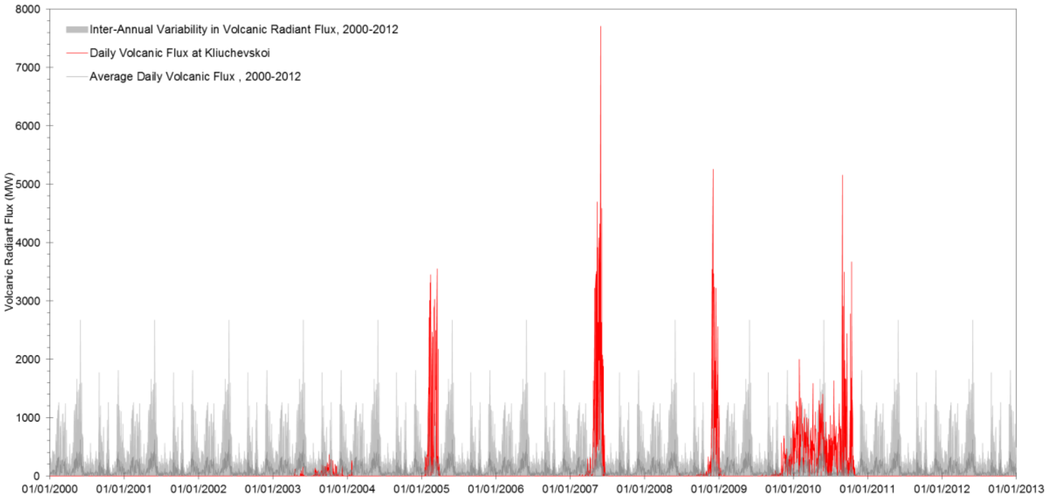
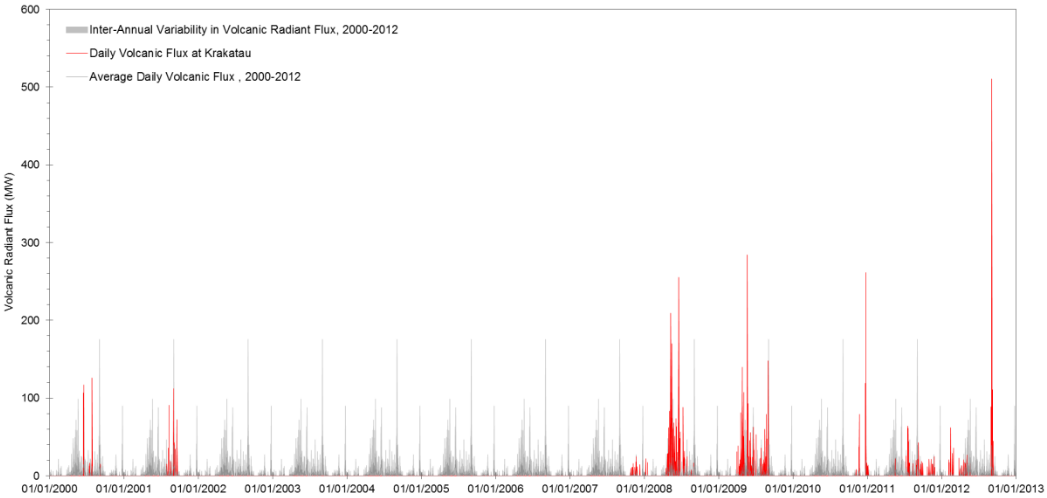
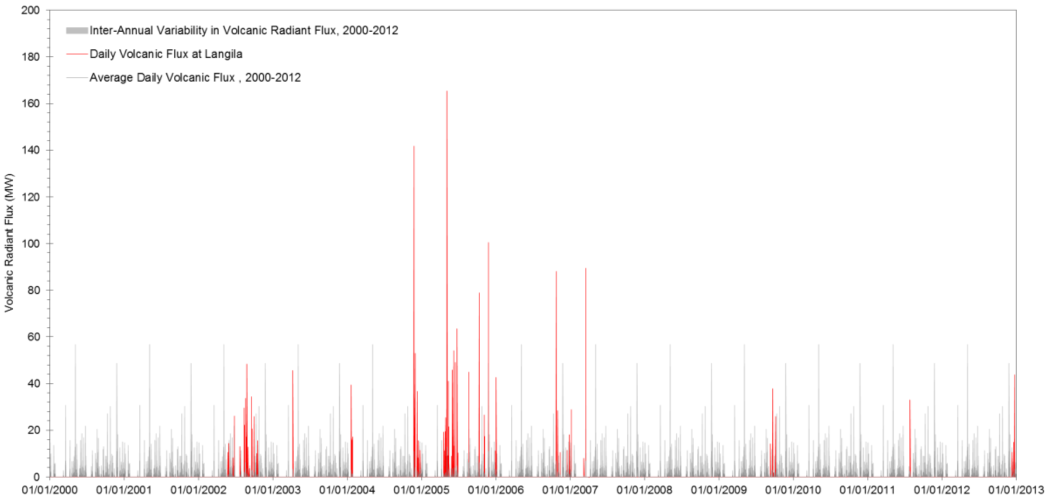
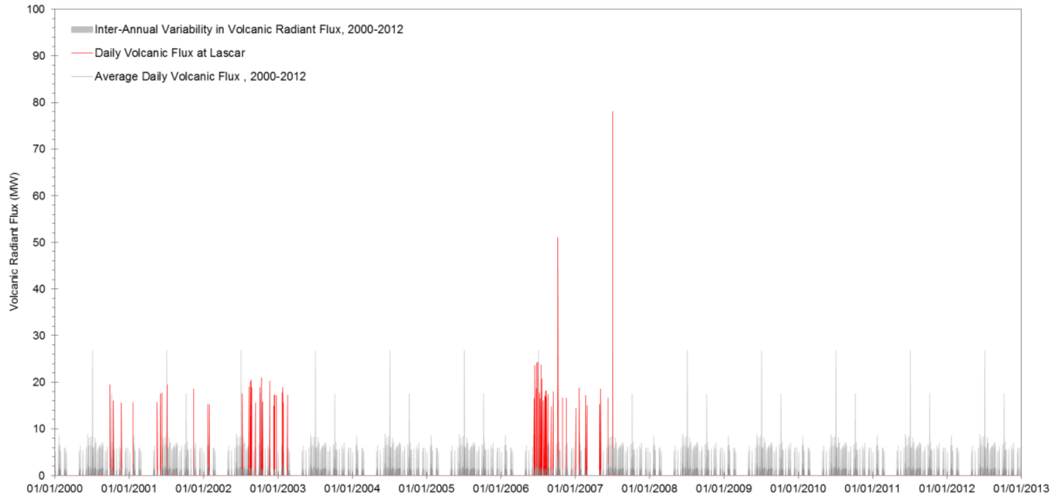
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Kliuchevskoi
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Krakatau
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Langila
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Lascar
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
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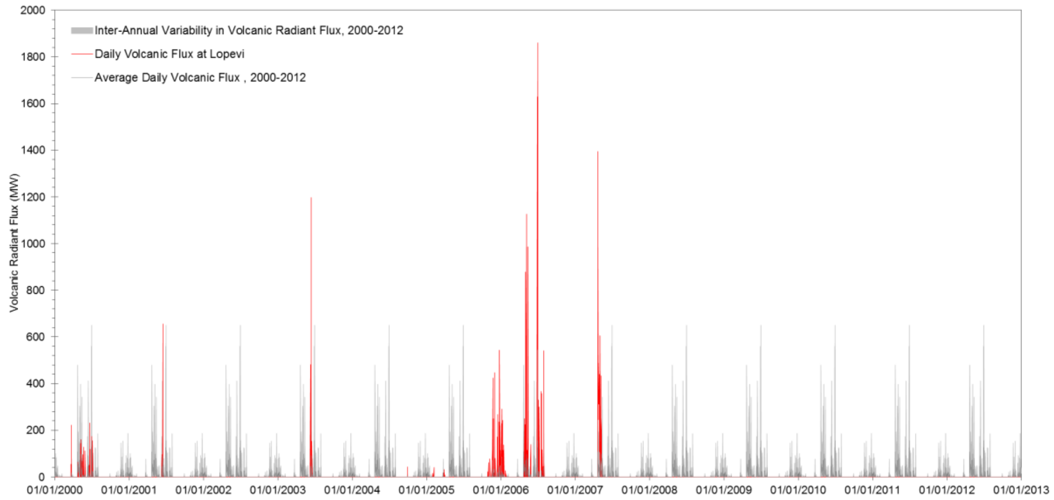
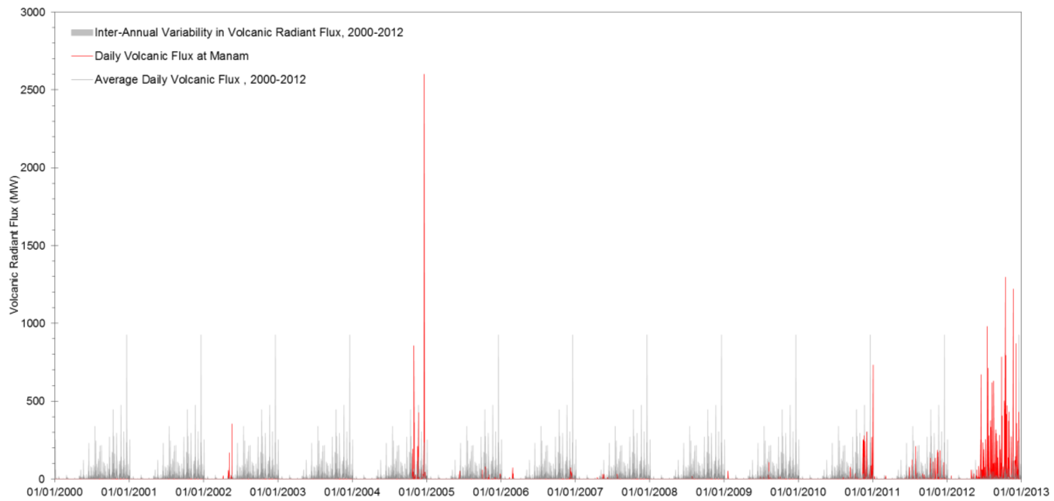
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Lopevi
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Manam
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
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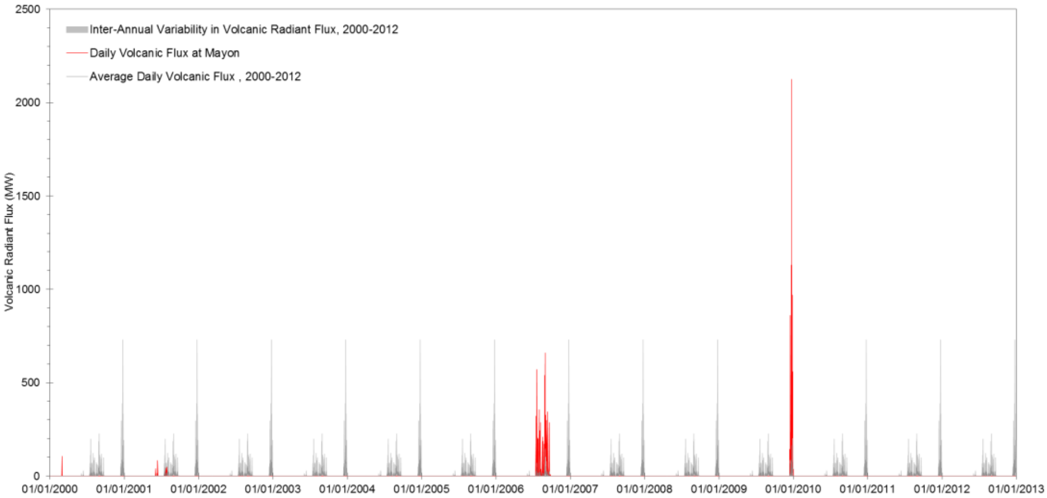
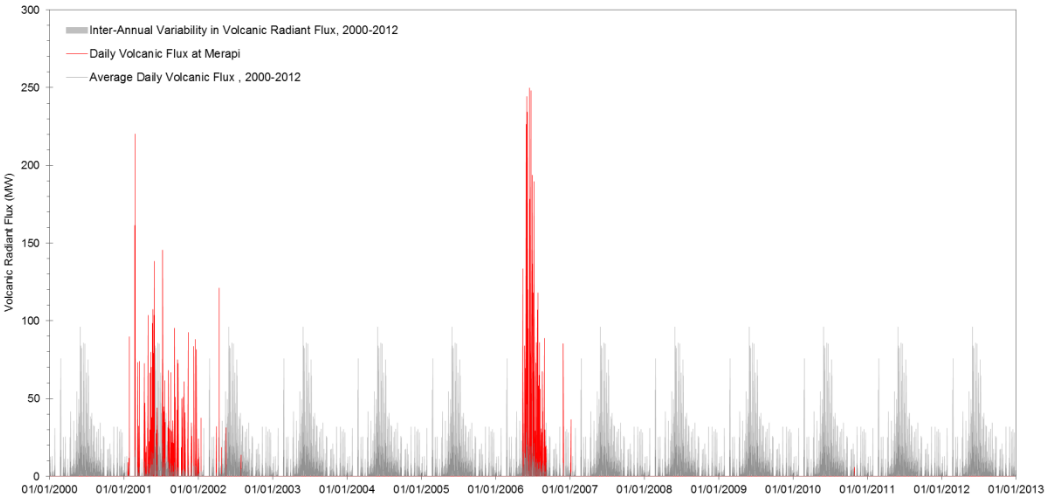
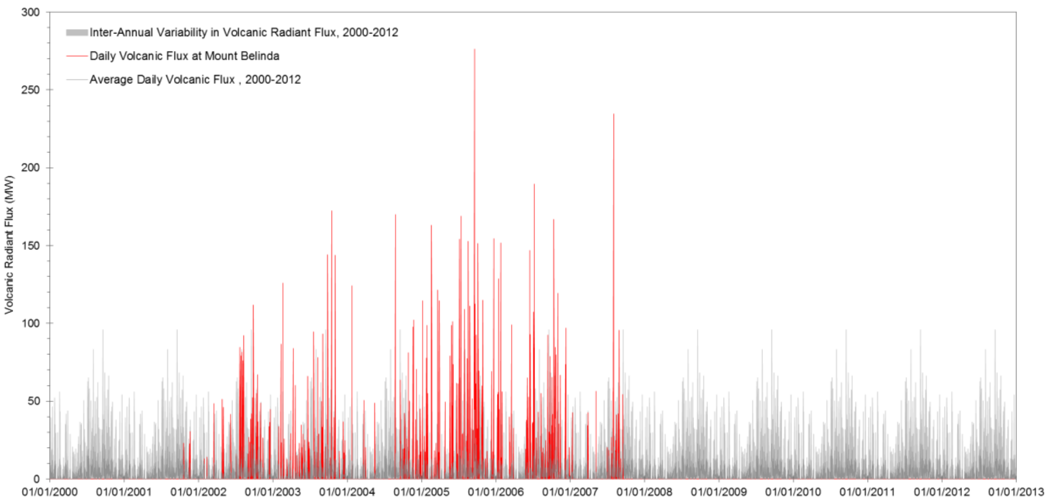
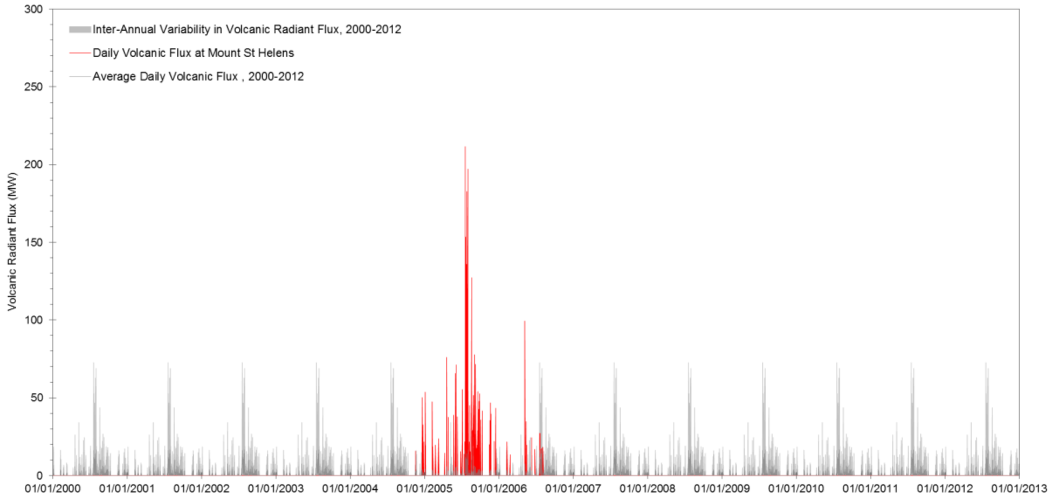
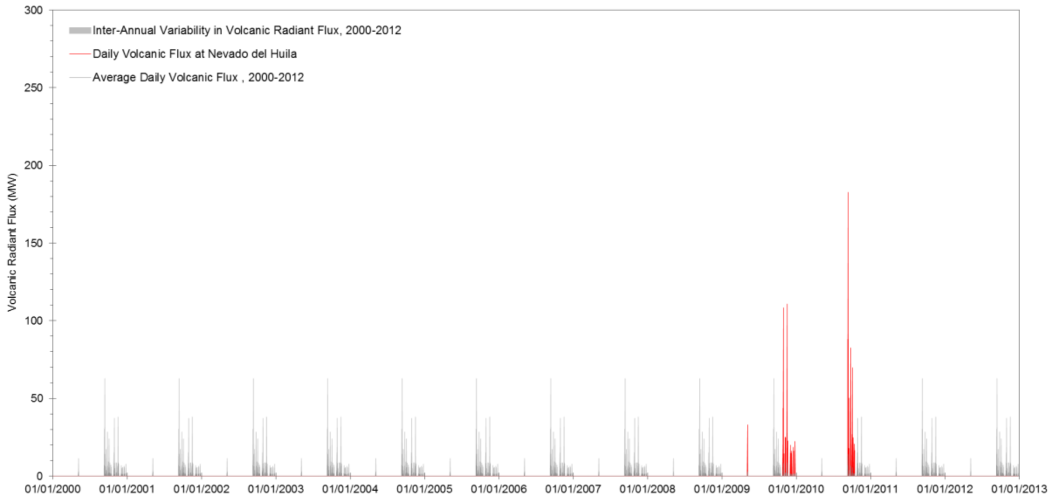
01/01/2012
01/01/2013

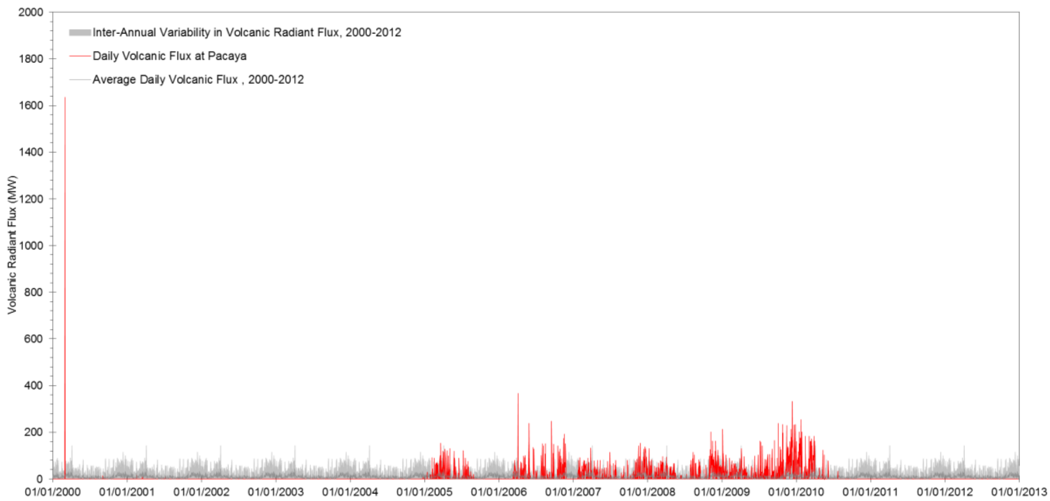

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Mayon
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
500
1000
1500
2000
2500
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

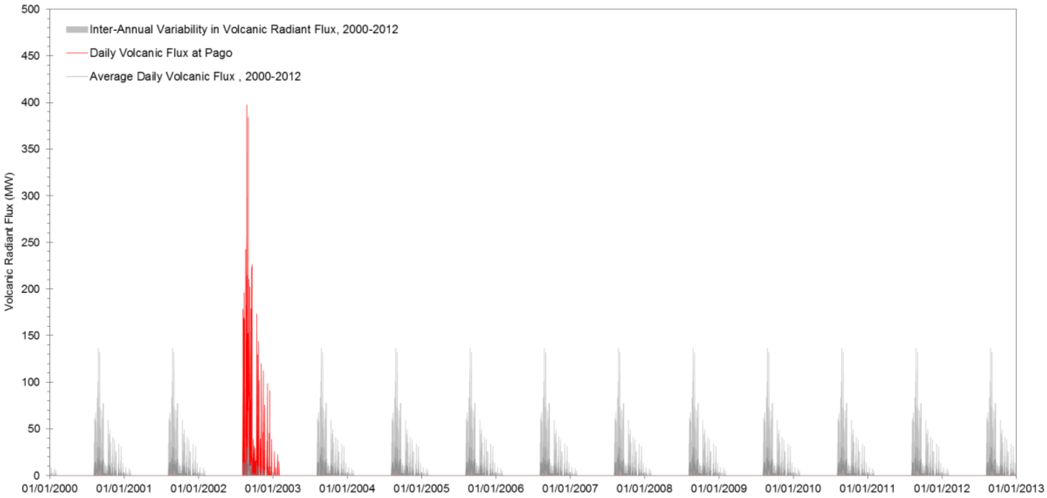

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Merapi
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

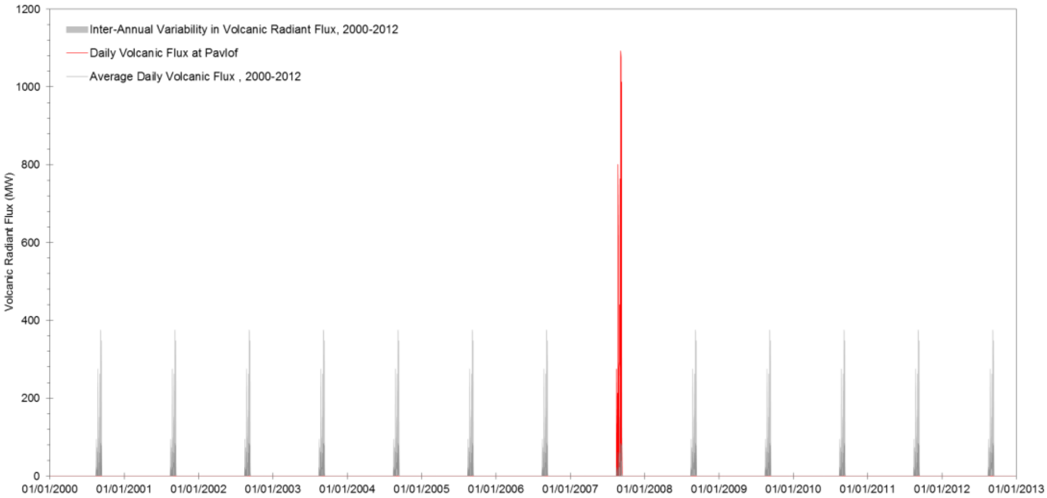

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Mount Belinda
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

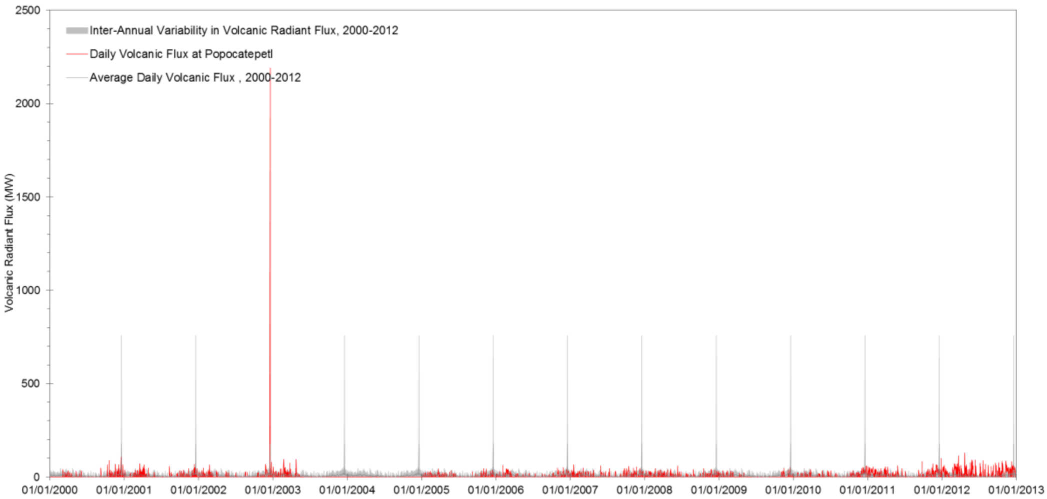

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Mount St Helens
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)

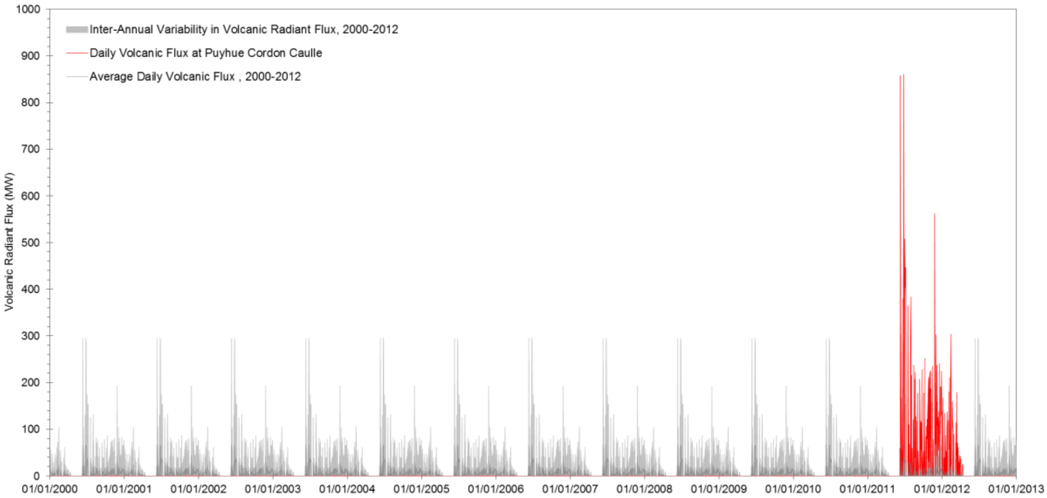

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Nevado del Huila
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)

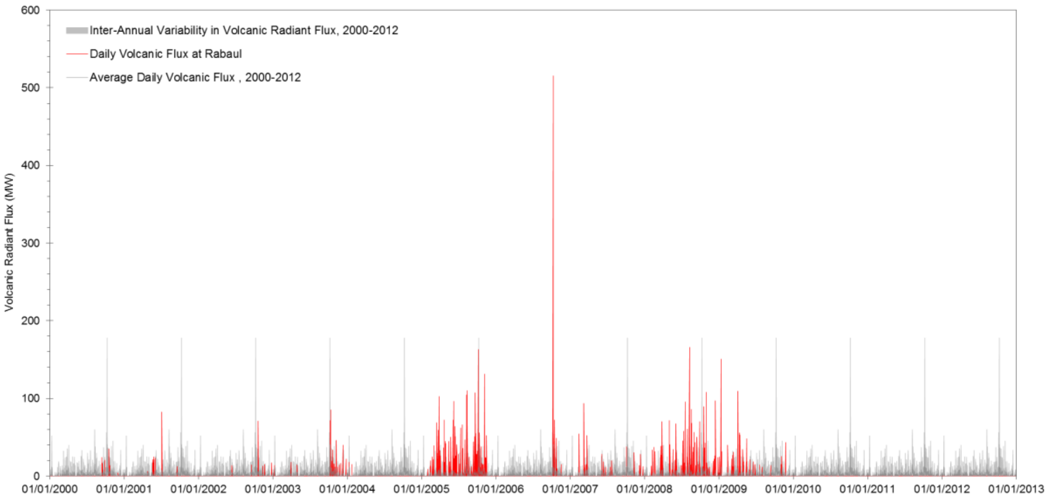

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Pacaya
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)

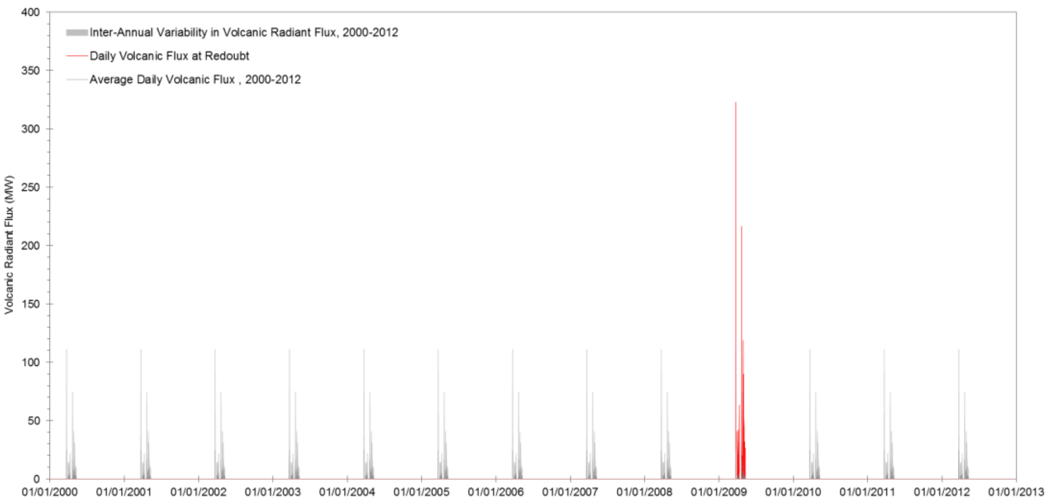

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Pago
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
350
400
450
500
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

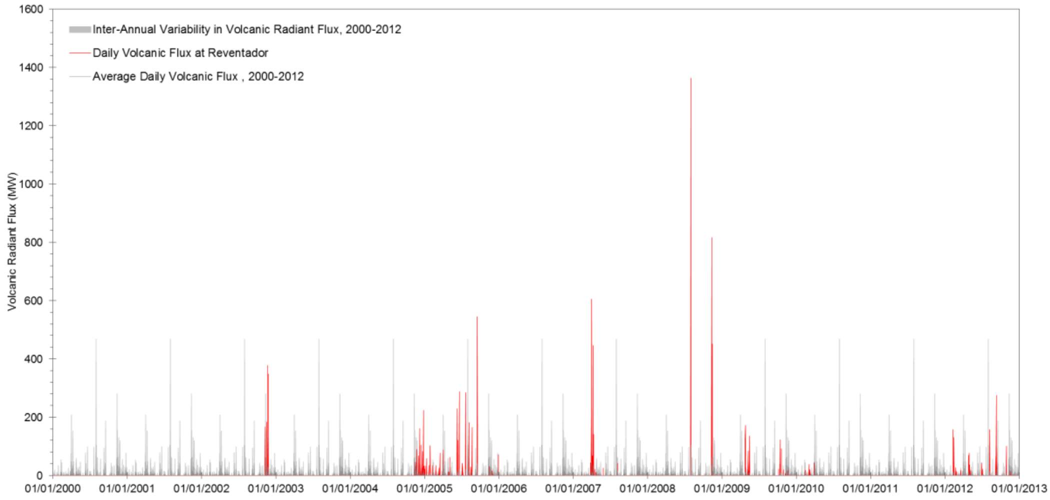

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Pavlof
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
200
400
600
800
1000
1200
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

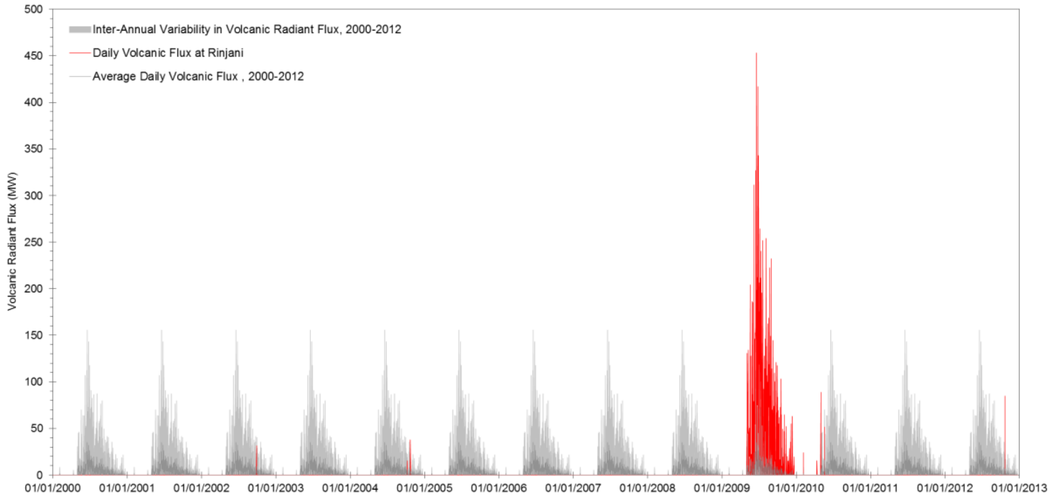

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Popocatepetl
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
500
1000
1500
2000
2500
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

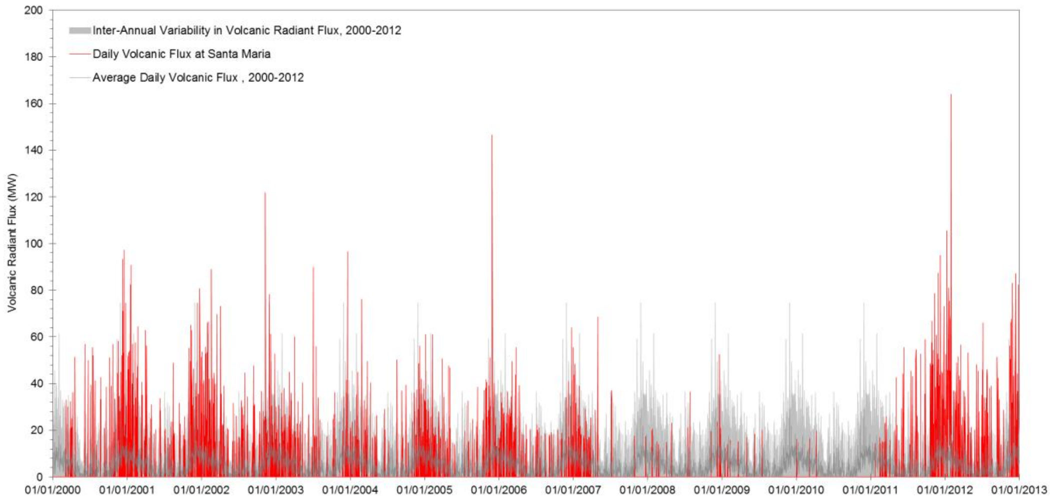

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Puyhue Cordon Caulle
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
1000
900
800
700
600
500
400
300
200
100
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

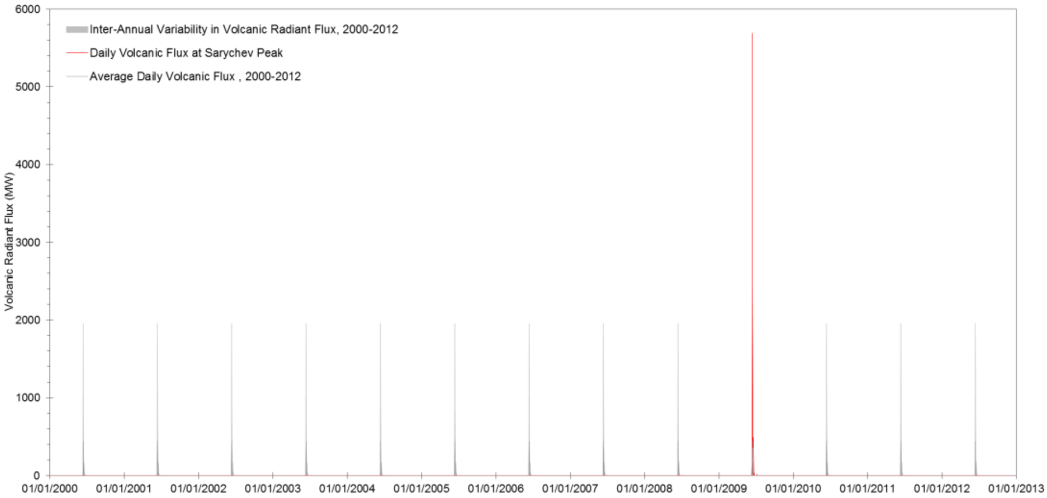

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Rabaul
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
600
500
400
300
200
100
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

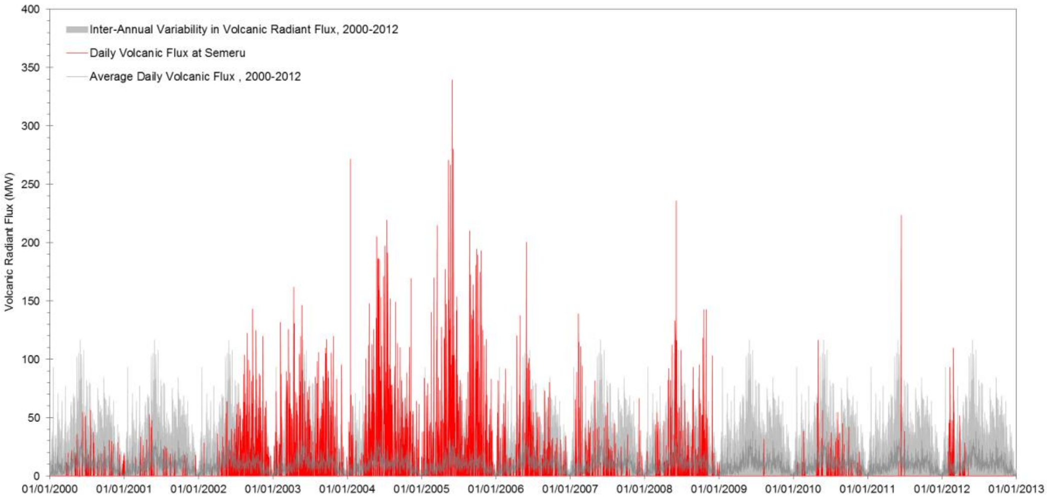

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Redoubt
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
400
350
300
250
200
150
100
50
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

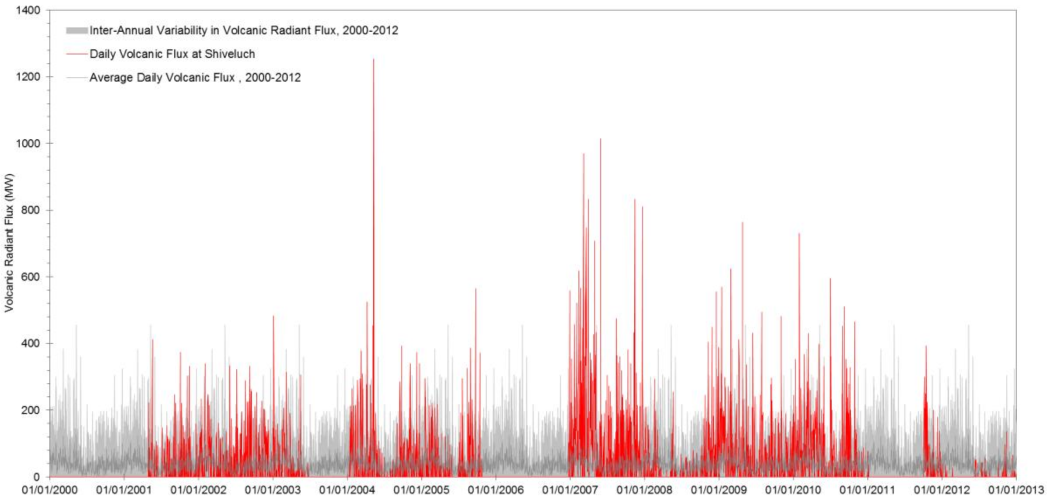

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Reventador
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
200
400
600
800
1000
1200
1400
1600
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

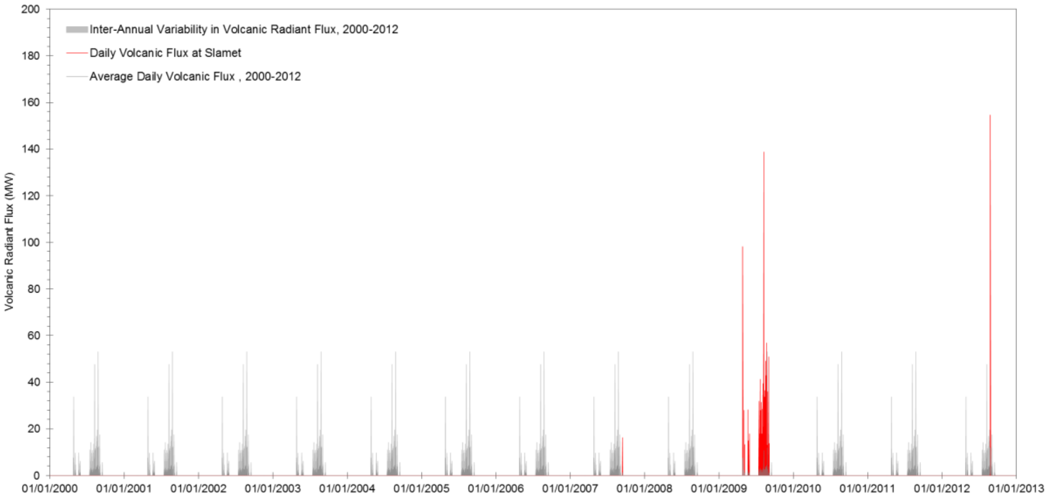

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Rinjani
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
50
100
150
200
250
300
350
400
450
500
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

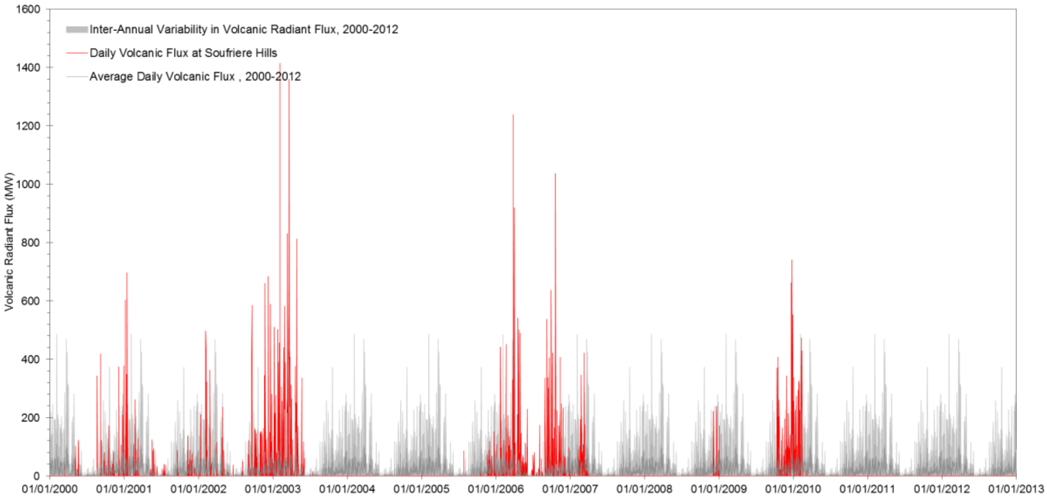

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Santa Maria
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
0
20
40
60
80
100
120
140
160
180
200
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Sarychev Peak
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
6000
5000
4000
3000
2000
1000
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Semeru
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
400
350
300
250
200
150
100
50
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Shiveluch
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
1400
1200
1000
800
600
400
200
0
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Slamet
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Soufriere Hills
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
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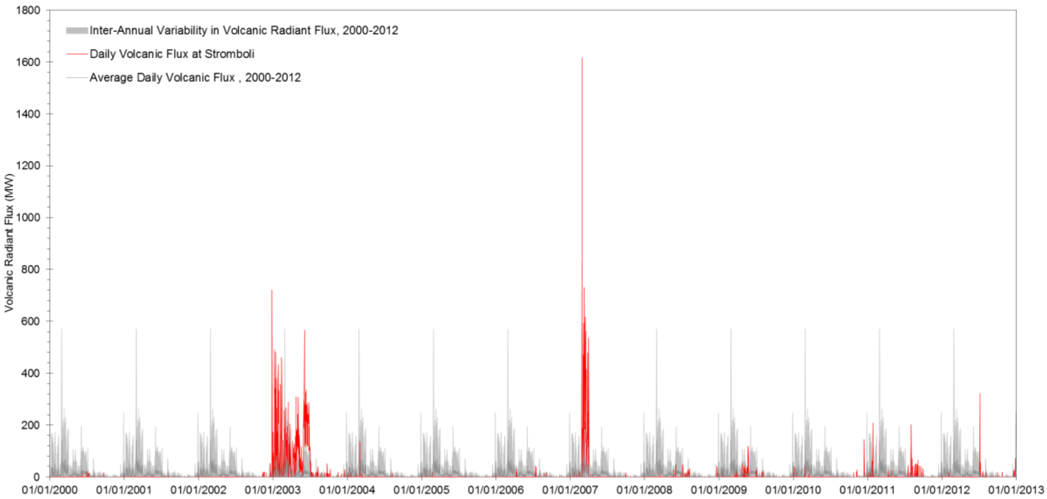
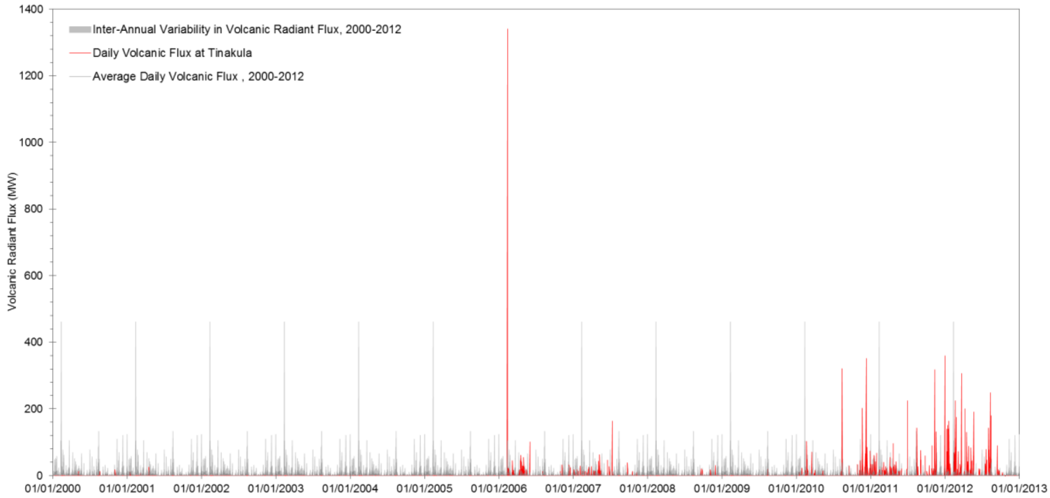
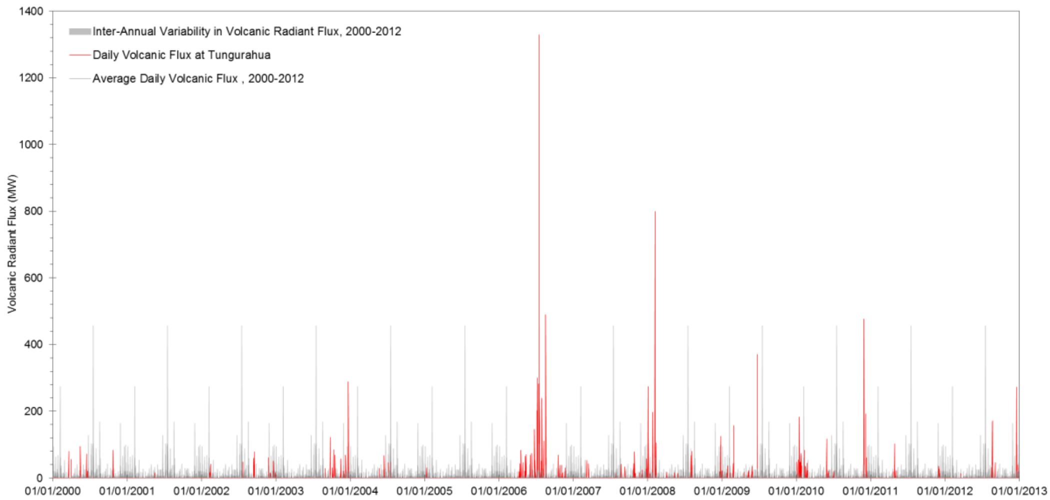
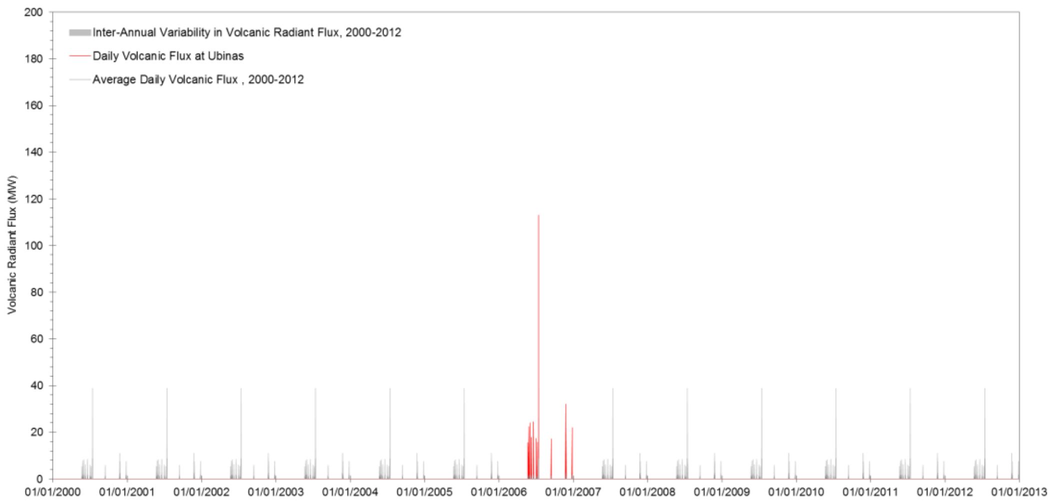
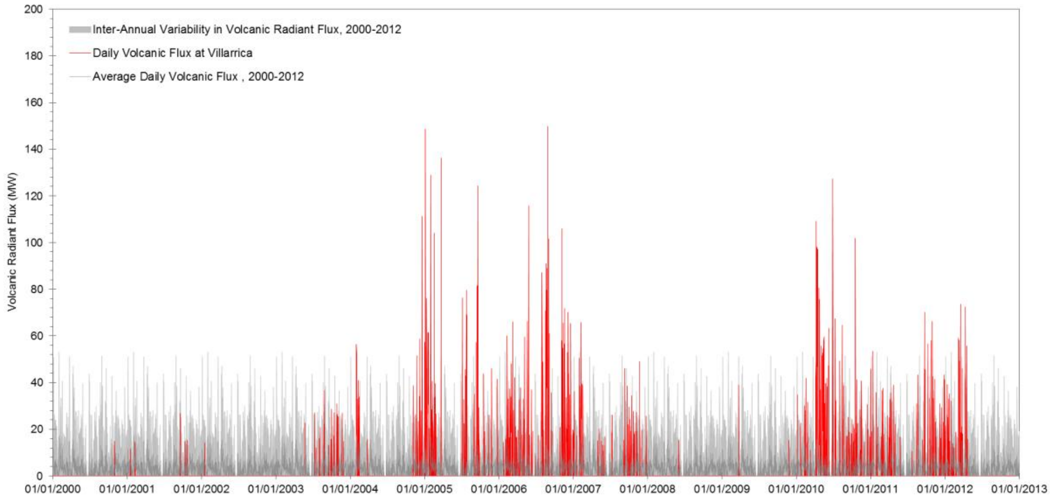
01/01/2011
01/01/2012
01/01/2013

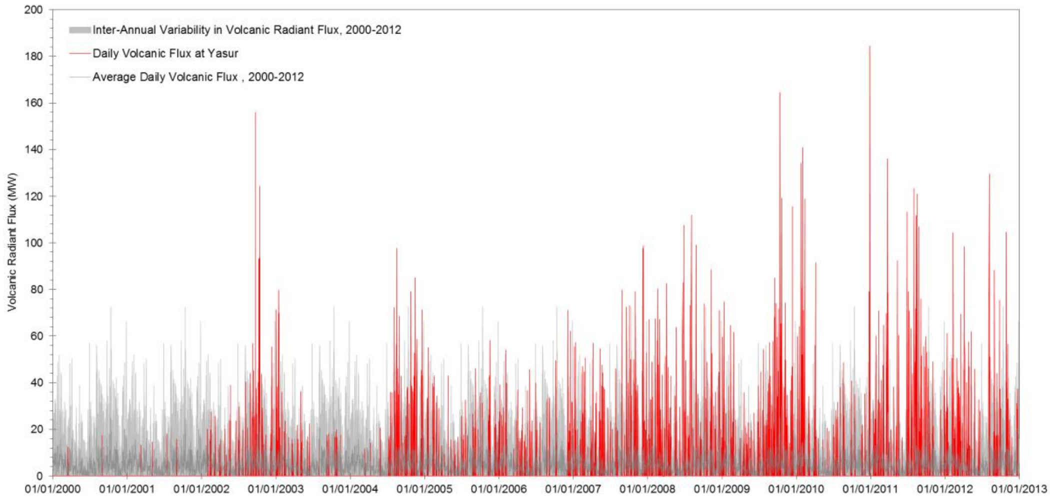

Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Stromboli
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Tinakula
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
1400
1200
1000
800
600
400
200
0
01/01/2000 01/01/2001 01/01/2002 01/01/2003 01/01/2004 01/01/2005 01/01/2006 01/01/2007 01/01/2008 01/01/2009 01/01/2010 01/01/2011 01/01/2012 01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Tungurahua
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
1400
1200
1000
800
600
400
200
0
01/01/2000 01/01/2001 01/01/2002 01/01/2003 01/01/2004 01/01/2005 01/01/2006 01/01/2007 01/01/2008 01/01/2009 01/01/2010 01/01/2011 01/01/2012 01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Ubinas
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
200
180
160
140
120
100
80
60
40
20
0
01/01/2000 01/01/2001 01/01/2002 01/01/2003 01/01/2004 01/01/2005 01/01/2006 01/01/2007 01/01/2008 01/01/2009 01/01/2010 01/01/2011 01/01/2012 01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Villarrica
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013


Inter-Annual Variability in Volcanic Radiant Flux, 2000-2012
Daily Volcanic Flux at Yasur
Average Daily Volcanic Flux , 2000-2012
Volcanic Radiant Flux (MW)
01/01/2000
01/01/2001
01/01/2002
01/01/2003
01/01/2004
01/01/2005
01/01/2006
01/01/2007
01/01/2008
01/01/2009
01/01/2010
01/01/2011
01/01/2012
01/01/2013

APPENDIX IV

PARAMETERS ASSOCIATED WITH ALL EARTHQUAKE-VOLCANO INTERACTIONS IDENTIFIED IN TABLE 5-1 - A) EARTHQUAKE PARAMETERS, B) VOLCANIC PARAMETERS AND C) SPATIAL PARAMETERS

A

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
1R	6.0	8.3	515.0	266	276	59	Normal	East	Indonesia	Converging	Eurasian
2R	6.3	13.4	14.0	289	19	78	Oblique Reverse	East	Russia	Transform	Okhotsk
3R	6.2	11.4	20.0	356	158	62	Reverse (Thrust)	South	Indonesia	Converging	Indo-Australian
4R	6.0	8.3	26.0	130	321	78	Strike-Slip	North West	Central America	Converging	North American
5R	6.0	8.3	20.8	278	125	84	Strike-Slip	East	Russia	Transform	North American
6R	6.4	15.7	84.0	119	129	16	Normal	North West	Central America	Transform	North American
7R	6.0	8.3	15.8	145	122	79	Oblique Reverse	North West	Indonesia	Converging	Indo-Australian
8R	6.2	11.4	40.0	274	223	18	Reverse (Thrust)	East	Indonesia	Converging	Indo-Australian
9R	6.2	11.4	40.0	284	223	18	Reverse (Thrust)	South East	Indonesia	Converging	Indo-Australian
10R	6.5	18.4	11.0	98	112	50	Reverse (Thrust)	West	Indonesia	Converging	Indo-Australian
11R	6.1	9.7	18.0	100	264	84	Oblique Reverse	North West	Indonesia	Transform	Indo-Australian
12R	6.1	9.7	14.0	250	20	40	Oblique Reverse	West	Antarctic	Converging	Scotia
13R	6.5	18.4	20.0	323	150	71	Oblique Reverse	South East	Central America	Converging	Cocos
14R	6.5	18.4	30.0	344	66	84	Oblique Reverse	South East	Indonesia	Converging	Philippines
15R	6.8	29.6	180.0	33	17	32	Oblique Reverse	South West	Russia	Converging	Okhotsk
16R	6.8	29.6	32.0	182	1	27	Reverse (Thrust)	North	South America	Converging	Nazca
17R	6.6	21.6	21.0	295	95	54	Oblique Reverse	South East	Russia	Transform	North American

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
18R	6.0	8.3	27.0	297	82	80	Strike-Slip	South East	Europe	Converging	African
19R	6.3	13.4	22.3	265	106	88	Oblique Reverse	East	Indonesia	Transform	Indo-Australian
20R	6.5	18.4	13.0	290	118	21	Reverse (Thrust)	South East	Indonesia	Converging	Eurasian
21R	6.5	18.4	13.0	293	118	21	Reverse (Thrust)	South East	Indonesia	Transform	Eurasian
22R	6.5	18.4	20.0	194	21	61	Oblique Reverse	North East	South America	Converging	South American
23R	6.1	9.7	61.7	229	169	31	Reverse (Thrust)	West	Antarctic	Converging	Scotia
24R	6.0	8.3	9.0	322	6	40	Normal	South East	Indonesia	Converging	Philippines
25R	6.9	34.8	35.0	307	311	26	Reverse (Thrust)	South East	Central America	Converging	Caribbean
26R	6.1	9.7	32.0	271	78	67	Reverse (Thrust)	East	Indonesia	Converging	Indo-Australian
27R	6.4	15.7	16.0	307	305	78	Oblique Reverse	South East	Caribbean	Converging	Caribbean
28R	6.2	11.4	11.0	18	37	68	Reverse (Thrust)	South West	Russia	Converging	Okhotsk
29R	6.3	13.4	17.5	295	99	61	Normal	South East	Indonesia	Converging	Indo-Australian
30R	6.1	9.7	22.3	130	5	90	Oblique Reverse	North West	Indonesia	Converging	Indo-Australian
31R	6.6	21.6	10.6	128	267	78	Strike-Slip	North West	Indonesia	Transform	Indo-Australian
32R	6.1	9.7	2.5	4	15	67	Oblique Reverse	South	Indonesia	Converging	Indian
33R	6.6	21.6	13.2	28	292	82	Strike-Slip	South West	North America	Transform	Juan de Fuca
34R	6.1	9.7	32.2	25	357	28	Reverse (Thrust)	South West	Indonesia	Converging	Indo-Australian
35R	6.1	9.7	51.2	23	206	20	Reverse (Thrust)	South East	Russia	Converging	Okhotsk
36R	6.8	29.6	154.2	334	7	77	Oblique Reverse	South East	South America	Converging	South American
37R	6.2	11.4	44.7	42	255	21	Reverse (Thrust)	South West	North America	Converging	North American
38R	6.4	15.7	50.7	357	325	18	Reverse (Thrust)	South	Indonesia	Converging	Eurasian
39R	6.4	15.7	23.0	344	168	60	Reverse (Thrust)	South	Indonesia	Converging	Indo-Australian
40R	6.2	11.4	14.0	184	174	79	Reverse (Thrust)	North	South America	Converging	Cocos
41R	6.6	21.6	12.0	41	11	14	Reverse (Thrust)	South West	South America	Converging	Nazca
42R	6.3	13.4	19.7	13	323	77	Strike-Slip	South	Indonesia	Converging	Eurasian
43R	6.3	13.4	26.0	34	53	61	Oblique Reverse	South West	Indonesia	Transform	Eurasian
44R	6.5	18.4	43.0	20	213	35	Reverse (Thrust)	South East	Russia	Converging	Okhotsk
45R	6.0	8.3	38.0	22	47	55	Reverse (Thrust)	South West	Russia	Converging	Okhotsk
46R	6.0	8.3	13.0	221	170	46	Oblique Reverse	North East	Indonesia	Transform	Eurasian
47R	6.2	11.4	8.0	170	38	36	Normal	North	South America	Converging	Cocos
48R	6.0	8.3	10.0	72	170	86	Strike-Slip	South West	South America	Transform	Antarctic

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
49R	6.1	9.7	10.0	48	60	68	Reverse (Thrust)	South West	North America	Converging	North American
50R	7.5	90.2	280.0	113	330	30	Oblique Reverse	North West	Indonesia	Converging	Eurasian
51R	6.8	29.6	21.0	117	321	12	Reverse (Thrust)	North West	Indonesia	Converging	Indo-Australian
52R	6.3	13.4	34.0	73	292	46	Reverse (Thrust)	South East	Indonesia	Transform	Indo-Australian
53R	6.2	11.4	9.9	287	250	71	Oblique Reverse	South East	Europe	Converging	African
54R	6.2	11.4	25.0	125	323	17	Reverse (Thrust)	North West	Indonesia	Converging	Indo-Australian
55R	6.0	8.3	22.0	6	230	14	Reverse (Thrust)	South	North America	Converging	North American
56R	6.4	15.7	16.0	281	301	74	Oblique Reverse	East	Europe	Converging	African
57R	6.1	9.7	15.0	55	225	55	Normal	South West	Indonesia	Converging	Indian
58R	6.3	13.4	173.9	341	232	41	Normal	South East	Indonesia	Converging	Eurasian
59R	6.9	34.8	110.0	158	0	39	Reverse (Thrust)	North	Indonesia	Converging	Indo-Australian
60R	6.1	9.7	23.0	133	289	68	Oblique Reverse	North West	Caribbean	Transform	Caribbean
61R	7.4	76.9	30.0	65	92	20	Reverse (Thrust)	South West	Indonesia	Converging	Eurasian
62R	6.3	13.4	24.0	110	331	19	Reverse (Thrust)	North West	Indonesia	Converging	Indo-Australian
63R	7.3	65.6	492.3	60	34	81	Normal	South West	Russia	Converging	Okhotsk
64R	6.4	15.7	398.0	262	129	63	Normal	East	Indonesia	Converging	Eurasian
65R	6.3	13.4	22.0	29	324	10	Reverse (Thrust)	South West	Indonesia	Converging	Indo-Australian
66R	6.2	11.4	152.0	4	208	89	Oblique Reverse	North East	Russia	Converging	Okhotsk
67R	6.4	15.7	14.0	42	91	83	Oblique Reverse	South West	Caribbean	Converging	Caribbean
68R	6.0	8.3	112.0	32	27	88	Oblique Reverse	South West	Russia	Converging	Okhotsk
69R	6.0	8.3	18.0	120	84	89	Strike-Slip	North West	Central America	Transform	Cocos
70R	6.1	9.7	38.8	342	18	78	Oblique Reverse	South	Indonesia	Converging	Eurasian
71R	6.4	15.7	45.0	335	8	106	Oblique Reverse	South East	Indonesia	Converging	Indo-Australian
72R	6.3	13.4	656.2	57	23	69	Oblique Reverse	South West	Russia	Converging	Okhotsk
73R	6.3	13.4	656.2	56	23	69	Oblique Reverse	South West	Russia	Converging	Okhotsk
74R	6.2	11.4	12.0	99	271	85	Strike-Slip	North West	Indonesia	Converging	Indo-Australian
75R	6.0	8.3	30.0	29	224	34	Oblique Reverse	South West	Russia	Converging	Okhotsk
76R	6.0	8.3	24.0	167	186	75	Reverse (Thrust)	North West	South America	Converging	Nazca
77R	6.3	13.4	20.0	104	124	78	Reverse (Thrust)	North West	Central America	Converging	North American
78R	6.3	13.4	23.0	6	34	63	Reverse (Thrust)	South	Russia	Converging	Okhotsk
79R	6.3	13.4	41.0	332	198	43	Reverse (Thrust)	South East	Indonesia	Converging	Eurasian

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
80R	6.2	11.4	10.0	87	289	86	Strike-Slip	West	Central America	Transform	Pacific
81R	7.8	145.2	20.1	116	316	8	Reverse (Thrust)	North West	Indonesia	Converging	Indo-Australian
82R	6.1	9.7	68.0	295	190	51	Reverse (Thrust)	South East	Indonesia	Converging	Indo-Australian
83R	6.8	29.6	470.0	298	326	78	Oblique Reverse	South East	East Asia	Converging	Philippines
84R	6.2	11.4	17.0	146	166	62	Reverse (Thrust)	North West	Indonesia	Converging	Indo-Australian
85R	6.3	13.4	21.0	158	1	17	Reverse (Thrust)	North West	South America	Converging	Nazca

B

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
1R	On-Going	2	326	0	Active	Stratovolcano	Intermediate	Andesite & Trachyandesite	Indonesia	Subduction Zone	Eurasian	Continental Crust
2R	On-Going	4	690	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
3R	On-Going	1	970	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
4R	New	3	125	0	Active	Stratovolcano (es)	Intermediate	Andesite	Mexico and Central America	Subduction Zone	North American	Continental Crust
5R	New	3	363	2	Latent	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
6R	On-Going	2	553	1	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Mexico and Central America	Subduction Zone	North American	Continental Crust
7R	On-Going	3	501	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
8R	New	2	147	2	Latent	Complex	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
9R	New	3	45	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
10R	On-Going	3	1630	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
11R	New	3	179	69	Latent	Caldera	Intermediate -Felsic	Andesite, Dacite & Rhyolite	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
12R	On-Going	1	107	0	Active	Shield	Mafic	Basalt	Antarctica	Subduction Zone	Scotia	Oceanic Crust
13R	On-Going	3	51	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt &Dacite	Mexico and Central America	Subduction Zone	Caribbean	Continental Crust
14R	New	3	19	11700	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachyandesite	Japan, Taiwan, Marianas	Subduction Zone	Philippine	Oceanic Crust
15R	On-Going	2	192	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
16R	On-Going	1	142	1	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt & Rhyolite	South America	Subduction Zone	South American	Continental Crust
17R	On-Going	4	504	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
18R	New	1	232	0	Active	Stratovolcano (es)	Intermediate -Mafic	Basalt, Trachyandesite & Trachybasalt	Mediterranean and W Asia	Subduction Zone	African	Continental Crust
19R	New	4	65	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
20R	New	0	79	3	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
21R	On-Going	2	42	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
22R	On-Going	1	141	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Rhyolite	South America	Subduction Zone	South American	Continental Crust
23R	On-Going	1	501	0	Active	Shield	Mafic	Basalt	Antarctica	Subduction Zone	Scotia	Oceanic Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
24R	On-Going	3	202	2	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachyandesite	Japan, Taiwan, Marianas	Subduction Zone	Philippine	Oceanic Crust
25R	On-Going	2	444	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Mexico and Central America	Subduction Zone	North American	Continental Crust
26R	On-Going	2	31	0	Active	Complex	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
27R	New	3	248	0	Active	Complex	Intermediate Complex	Andesite, Basalt, Dacite & Rhyolite	Mexico and Central America	Subduction Zone	North American	Continental Crust
28R	On-Going	2	74	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
29R	On-Going	2	289	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
30R	On-Going	2	600	0	Active	Lava cone	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
31R	On-Going	2	70	0	Active	Complex	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
32R	New	2	410	10	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
33R	On-Going	2	107	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite, Trachyandesite & Trachybasalt	Canada and Western USA	Subduction Zone	North American	Continental Crust
34R	On-Going	2	91	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
35R	On-Going	3	251	0	Active	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
36R	New	2	53	37	Latent	Stratovolcano	Intermediate -Felsic	Andesite, Dacite Rhyolite & Trachyandesite	South America	Subduction Zone	South American	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
37R	New	3	93	20	Latent	Lava dome(s)	Intermediate -Felsic	Andesite & Dacite	Alaska	Subduction Zone	North American	Continental Crust
38R	New	1	73	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Philippines and SE Asia	Subduction Zone	Eurasian	Continental Crust
39R	New	2	111	4	Latent	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
40R	New	3	133	0	Active	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	South America	Subduction Zone	South American	Continental Crust
41R	New	3	159	1	Latent	Stratovolcano (es)	Intermediate -Felsic	Andesite & Dacite	South America	Subduction Zone	South American	Continental Crust
42R	On-Going	1	103	4	Latent	Stratovolcano	Intermediate	Andesite & Trachyandesite	Indonesia	Subduction Zone	Eurasian	Continental Crust
43R	On-Going	1	80	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
44R	On-Going	4	1474	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
45R	New	2	137	2	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
46R	New	2	1075	155	Latent	Stratovolcano	Intermediate -Mafic	Trachyandesite & Trachybasalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
47R	New	2	28	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	South America	Subduction Zone	South American	Continental Crust
48R	New	4	454	368	Latent	Caldera	Felsic	Rhyolite	South America	Subduction Zone	South American	Continental Crust
49R	New	2	28	10	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Alaska	Subduction Zone	North American	Continental Crust
50R	New	2	67	17	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
51R	New	2	83	6	Latent	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
52R	On-Going	4	57	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
53R	On-Going	1	419	0	Active	Stratovolcano (es)	Intermediate -Mafic	Basalt, Trachyandesite & Trachybasalt	Mediterranean and W Asia	Subduction Zone	African	Continental Crust
54R	On-Going	2	138	0	Active	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust
55R	New	3	48	19	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Alaska	Subduction Zone	North American	Continental Crust
56R	On-Going	2	42	0	Active	Stratovolcano	Intermediate -Mafic	Andesite, Basalt & Trachyandesite	Mediterranean and W Asia	Subduction Zone	Eurasian	Continental Crust
57R	On-Going	2	594	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
58R	On-Going	1	102	3	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
59R	On-Going	2	360	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
60R	New	3	32	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	West Indies	Subduction Zone	Caribbean	Oceanic Crust
61R	New	2	54	1	Latent	Stratovolcano	Intermediate -Mafic	Andesite and Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
62R	New	1	33	10	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust
63R	On-Going	1	64	1	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
64R	New	2	232	5	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachybasalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
65R	New	1	53	1	Latent	Stratovolcano	Intermediate	Andesite	Indonesia	Subduction Zone	Eurasian	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
66R	New	4	26	20	Latent	Stratovolcano	Intermediate	Andesite	Kuril Islands	Subduction Zone	Okhotsk	Intermediate Crust
67R	On-Going	3	151	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	West Indies	Subduction Zone	Caribbean	Oceanic Crust
68R	On-Going	3	46	0	Active	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
69R	On-Going	3	61	0	Active	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	South America	Subduction Zone	South American	Continental Crust
70R	New	2	18	1	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Philippines and SE Asia	Subduction Zone	Eurasian	Continental Crust
71R	On-Going	2	931	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
72R	New	3	10	1	Latent	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
73R	On-Going	2	415	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
74R	On-Going	1	76	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
75R	New	1	65	24	Latent	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
76R	On-Going	1	416	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Rhyolite	South America	Subduction Zone	South American	Continental Crust
77R	On-Going	3	710	0	Active	Stratovolcano	Intermediate -Felsic	Andesite & Dacite	Mexico and Central America	Subduction Zone	North American	Continental Crust
78R	New	3	472	82	Latent	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
79R	On-Going	3	65	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
80R	On-Going	2	286	0	Active	Stratovolcano (es)	Intermediate Complex	Andesite, Basalt & Dacite	Mexico and Central America	Subduction Zone	North American	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Length of Volcanic Response (Days)	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
81R	New	2	60	1	Latent	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust
82R	On-Going	2	49	0	Active	Stratovolcano	Intermediate -Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
83R	New	2	31	0	Active	Shield	Intermediate Complex	Andesite, Basalt & Dacite	Japan, Taiwan, Marianas	Subduction Zone	Eurasian	Continental Crust
84R	On-Going	3	230	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
85R	New	5	310	21	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Rhyolite	South America	Subduction Zone	South American	Continental Crust

C

Event ID	Temporal Delay Between Triggering Earthquake and Responding Volcano (Days)	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
1R	7	772	Along	Compression
2R	1	152	Perpendicular	Dilatation
3R	2	245	Along	Compression
4R	95	470	Along/Perpendicular	Compression
5R	67	725	Along	Compression
6R	38	274	Along	Compression
7R	16	298	Along	Compression
8R	86	331	Along	Compression
9R	38	729	Along	Compression
10R	1	997	Along/Perpendicular	Compression
11R	34	338	Along	Compression
12R	1	186	Perpendicular	Compression

Event ID	Temporal Delay Between Triggering Earthquake and Responding Volcano (Days)	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
13R	42	351	Along	Compression
14R	269	261	Perpendicular	Dilatation
15R	33	80	Along	Compression
16R	20	974	Along/Perpendicular	Compression
17R	37	297	Perpendicular	Dilatation
18R	177	833	Along	Dilatation
19R	161	640	Along	Dilatation
20R	27	645	Perpendicular	Compression
21R	80	928	Perpendicular	Compression
22R	69	516	Along	Compression
23R	6	71	Perpendicular	Dilatation
24R	94	246	Perpendicular	Compression
25R	3	567	Along	Compression
26R	8	343	Along	Compression
27R	34	882	Along	Dilatation
28R	29	857	Along	Compression
29R	9	903	Along	Compression
30R	4	281	Along	Compression
31R	8	353	Perpendicular	Compression
32R	8	758	Along/Perpendicular	Dilatation
33R	9	711	Perpendicular	Compression
34R	32	121	Perpendicular	Compression
35R	39	887	Along	Dilatation
36R	187	739	Along	Dilatation
37R	58	894	Along/Perpendicular	Dilatation
38R	227	776	Along	Compression
39R	19	811	Along	Compression
40R	75	926	Perpendicular	Dilatation
41R	43	540	Perpendicular	Compression
42R	1	48	Perpendicular	Dilatation
43R	18	427	Perpendicular	Compression

Event ID	Temporal Delay Between Triggering Earthquake and Responding Volcano (Days)	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
44R	123	662	Along	Compression
45R	50	945	Along	Compression
46R	6	612	Perpendicular	Dilatation
47R	8	524	Perpendicular	Compression
48R	362	679	Along/Perpendicular	Compression
49R	31	520	Along/Perpendicular	Compression
50R	102	587	Along	Compression
51R	3	546	Along/Perpendicular	Compression
52R	32	617	Perpendicular	Dilatation
53R	81	624	Along	Compression
54R	43	758	Along/Perpendicular	Compression
55R	302	493	Perpendicular	Compression
56R	20	560	Along	Dilatation
57R	2	283	Perpendicular	Compression
58R	33	868	Perpendicular	Compression
59R	43	329	Along	Dilatation
60R	53	390	Perpendicular	Compression
61R	16	404	Along	Dilatation
62R	156	937	Along/Perpendicular	Compression
63R	1	453	Along	Compression
64R	148	920	Along	Compression
65R	13	180	Perpendicular	Compression
66R	51	332	Along	Compression
67R	29	910	Perpendicular	Compression
68R	13	846	Along	Compression
69R	4	839	Perpendicular	Compression
70R	16	922	Along	Compression
71R	32	718	Along	Compression
72R	7	579	Along	Compression
73R	5	586	Along	Compression
74R	8	907	Along	Dilatation

Event ID	Temporal Delay Between Triggering Earthquake and Responding Volcano (Days)	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
75R	130	742	Along	Dilatation
76R	4	364	Along/Perpendicular	Compression
77R	206	692	Along	Compression
78R	133	294	Perpendicular	Compression
79R	13	193	Perpendicular	Dilatation
80R	30	903	Perpendicular	Compression
81R	12	659	Along/Perpendicular	Compression
82R	1	483	Along	Dilatation
83R	57	895	Perpendicular	Dilatation
84R	2	302	Along	Compression
85R	7	361	Along/Perpendicular	Compression

APPENDIX V

PARAMETERS ASSOCIATED WITH ALL NON-RESPONSE EARTHQUAKE-VOLCANO INTERACTIONS IDENTIFIED IN TABLE 5-3 - A) EARTHQUAKE PARAMETERS, B) VOLCANIC PARAMETERS AND C) SPATIAL PARAMETERS

A

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
1NR	6.3	13.4	140.0	290	300	79	Oblique Reverse	North West	Indonesia	Converging	Eurasian
2NR	6.0	8.3	17.0	208	177	20	Reverse (Thrust)	South West	Asia	Converging	Philippines
3NR	6.1	9.7	18.6	304	54	54	Normal	North West	Indonesia	Converging	Indo-Australian
4NR	6.6	21.6	135.0	232	63	64	Oblique Reverse	South West	North America	Converging	North American
5NR	6.3	13.4	14.0	266	19	78	Oblique Reverse	South West	Russia	Transform	Okhotsk
6NR	7.5	90.2	31.0	160	156	67	Reverse (Thrust)	South East	Indonesia	Converging	Eurasian
7NR	6.1	9.7	11.0	166	355	56	Oblique Reverse	South East	Indonesia	Converging	Indo-Australian
8NR	6.3	13.4	18.0	34	71	73	Reverse (Thrust)	South West	North America	Converging	North American
9NR	6.1	9.7	18.0	80	172	75	Oblique Reverse	North East	Indonesia	Transform	Indo-Australian
10NR	6.2	11.4	20.0	160	357	43	Reverse (Thrust)	South East	Indonesia	Transform	Eurasian
11NR	6.0	8.3	19.2	109	324	78	Strike-Slip	South East	Indonesia	Converging	Eurasian
12NR	6.6	21.6	15.0	114	124	53	Reverse (Thrust)	East	Antarctic	Transform	Scotia
13NR	6.4	15.7	24.0	17	122	58	Reverse (Thrust)	North	Central America	Transform	North American
14NR	6.3	13.4	32.0	16	123	39	Reverse (Thrust)	North East	Indonesia	Converging	Indo-Australian
15NR	6.8	29.6	180.0	33	123	32	Oblique Reverse	North East	Russia	Converging	Okhotsk

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
16NR	6.2	11.4	11.0	256	285	85	Oblique Reverse	South West	Europe	Transform	African
17NR	6.5	18.4	18.0	193	8	71	Oblique Reverse	South	Asia	Transform	Eurasian
18NR	6.3	13.4	381.0	254	50	34	Oblique Reverse	South West	Asia	Converging	Eurasian
19NR	6.6	21.6	21.0	249	95	54	Oblique Reverse	South West	Russia	Transform	North American
20NR	6.2	11.4	24.0	71	282	30	Oblique Reverse	West	North America	Converging	North American
21NR	6.2	11.4	28.0	306	121	74	Reverse (Thrust)	North West	Central America	Converging	Caribbean
22NR	7.3	65.6	580.9	128	108	45	Oblique Reverse	South East	Indonesia	Transform	Eurasian
23NR	6.5	18.4	20.0	194	21	61	Oblique Reverse	South	South America	Converging	South American
24NR	6.0	8.3	9.0	341	6	40	Normal	North East	Indonesia	Converging	Philippines
25NR	6.2	11.4	11.0	19	223	23	Reverse (Thrust)	North East	Russia	Converging	Okhotsk
26NR	6.7	25.3	19.0	127	142	34	Reverse (Thrust)	South East	Indonesia	Converging	Indo-Australian
27NR	6.5	18.4	17.0	73	80	89	Strike-Slip	South West	South America	Transform	Antarctic
28NR	6.5	18.4	17.0	52	80	89	Strike-Slip	North East	South America	Transform	Antarctic
29NR	6.1	9.7	9.7	355	0	81	Strike-Slip	North	Australia	Converging	Indo-Australian
30NR	6.4	15.7	50.7	158	325	18	Reverse (Thrust)	South East	Indonesia	Converging	Eurasian
31NR	6.8	29.6	16.7	353	149	50	Normal	South	Africa	Diverging	African
32NR	6.7	25.3	66.0	284	201	44	Oblique Reverse	North West	Europe	Converging	Eurasian
33NR	6.4	15.7	23.0	16	168	60	Reverse (Thrust)	North East	Indonesia	Converging	Indo-Australian
34NR	6.0	8.3	10.0	248	97	81	Strike-Slip	South West	South America	Ridge	Cocos
35NR	6.3	13.4	19.7	94	323	77	Oblique Reverse	South	Indonesia	Converging	Eurasian
36NR	6.5	18.4	34.0	273	243	34	Reverse (Thrust)	West	Indonesia	Converging	Indo-Australian
37NR	7.7	123.9	24.3	74	98	80	Reverse (Thrust)	North East	Indonesia	Converging	Indo-Australian
38NR	6.4	15.7	28.2	116	129	88	Strike-Slip	South East	Indonesia	Converging	Indo-Australian
39NR	6.8	29.6	150.0	157	31	68	Oblique Reverse	South	Indonesia	Converging	Indo-Australian
40NR	6.0	8.3	56.0	292	97	33	Normal	South East	Central America	Converging	North American

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
41NR	6.0	8.3	56.0	77	97	33	Normal	East	Central America	Converging	North American
42NR	6.1	9.7	53.0	356	14	28	Oblique Reverse	North	Caribbean	Converging	Caribbean
43NR	6.3	13.4	204.0	157	191	86	Oblique Reverse	South East	Indonesia	Transform	Eurasian
44NR	6.6	21.6	20.0	170	128	37	Oblique Reverse	South	Asia	Converging	Philippines
45NR	6.3	13.4	23.0	20	167	75	Reverse (Thrust)	North East	South America	Converging	South American
46NR	6.1	9.7	10.0	155	81	37	Oblique Reverse	South East	Antarctic	Transform	Scotia
47NR	6.3	13.4	25.7	265	130	89	Strike-Slip	West	Indonesia	Transform	Indo-Australian
48NR	6.8	29.6	350.4	215	27	83	Oblique Reverse	South West	Asia	Converging	Eurasian
49NR	7.5	90.2	280.0	108	330	30	Oblique Reverse	South East	Indonesia	Transform	Eurasian
50NR	6.6	21.6	16.0	81	157	75	Oblique Reverse	East	Indonesia	Converging	Indo-Australian
51NR	7.4	76.9	156.0	334	109	58	Oblique Reverse	North	Caribbean	Converging	Caribbean
52NR	6.4	15.7	25.0	50	62	69	Reverse (Thrust)	South West	North America	Converging	North American
53NR	6.2	11.4	8.0	1	70	38	Oblique Reverse	North	Indonesia	Converging	Eurasian
54NR	6.5	18.4	83.0	303	178	35	Normal	North West	Central America	Converging	North American
55NR	6.1	9.7	33.0	322	44	45	Oblique Reverse	North West	Central America	Converging	North American
56NR	6.3	13.4	9.0	92	267	78	Oblique Reverse	East	Iceland	Ridge	North American
57NR	6.3	13.4	31.0	161	206	71	Oblique Reverse	South	Indonesia	Converging	Eurasian
58NR	6.0	8.3	14.0	269	88	23	Reverse (Thrust)	West	Indonesia	Converging	Eurasian
59NR	7.7	123.9	632.8	150	143	48	Oblique Reverse	South East	Russia	Converging	Okhotsk
60NR	6.2	11.4	27.0	20	46	57	Reverse (Thrust)	North East	Russia	Converging	Okhotsk
61NR	6.0	8.3	10.0	299	293	74	Oblique Reverse	South East	Indonesia	Converging	Indo-Australian
62NR	6.4	15.7	154.0	336	198	39	Oblique Reverse	North West	South America	Converging	South American
63NR	6.7	25.3	24.0	87	127	65	Reverse (Thrust)	North East	Central America	Converging	North American
64NR	6.2	11.4	18.0	182	360	19	Reverse (Thrust)	South	South America	Converging	Nazca

Event ID	Earthquake Magnitude	Earthquake Rupture Length (km)	Earthquake Depth (km)	Earthquake Azimuth to Volcano (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Setting of Earthquake's Location	Tectonic Plate of Earthquake's Location
65NR	6.3	13.4	206.0	176	228	17	Reverse (Thrust)	South	Indonesia	Converging	Eurasian
66NR	6.2	11.4	23.0	356	101	44	Normal	North	Indonesia	Converging	Indo-Australian
67NR	6.6	21.6	17.0	131	260	74	Oblique Reverse	South East	North America	Transform	Pacific
68NR	6.1	9.7	38.8	199	148	19	Oblique Reverse	South West	Indonesia	Converging	Eurasian
69NR	6.0	8.3	15.0	295	77	48	Oblique Reverse	North West	Indonesia	Converging	Eurasian
70NR	6.3	13.4	656.2	53	23	69	Oblique Reverse	North East	Russia	Converging	Okhotsk
71NR	6.2	11.4	28.0	39	22	68	Reverse (Thrust)	North East	Russia	Converging	Okhotsk
72NR	6.3	13.4	115.0	159	167	40	Normal	South East	South America	Converging	South American
73NR	6.4	15.7	18.0	297	65	76	Oblique Reverse	West	Russia	Transform	North American
74NR	7.2	56.0	24.0	134	5	13	Reverse (Thrust)	East	South America	Converging	South American
75NR	6.1	9.7	16.2	177	110	71	Oblique Reverse	South	Indonesia	Transform	Eurasian
76NR	6.0	8.3	20.0	172	14	21	Reverse (Thrust)	South	South America	Converging	Nazca
77NR	6.1	9.7	36.0	24	32	55	Reverse (Thrust)	North East	Russia	Converging	Okhotsk
78NR	6.3	13.4	10.0	92	119	86	Strike-Slip	West	Central America	Ridge	Pacific
79NR	6.3	13.4	17.0	338	284	35	Oblique Reverse	North West	Indonesia	Converging	Eurasian
80NR	6.2	11.4	116.0	158	138	48	Reverse (Thrust)	South East	Antarctic	Transform	Scotia

B

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
1NR	No Response	0	0	Active	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
2NR	No Response	0	11700	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachyandesite	Japan, Taiwan, Marianas	Subduction Zone	Philippine	Oceanic Crust
3NR	No Response	0	68	Latent	Caldera	Intermediate-Felsic	Andesite, Dacite & Rhyolite	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
4NR	No Response	0	2	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Alaska	Subduction Zone	North American	Continental Crust
5NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
6NR	No Response	3	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
7NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
8NR	No Response	0	16	Latent	Lava dome(s)	Intermediate-Felsic	Andesite & Dacite	Alaska	Subduction Zone	North American	Continental Crust
9NR	No Response	0	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
10NR	No Response	0	150	Latent	Stratovolcano	Intermediate-Mafic	Trachyandesite & Trachybasalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
11NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Philippines and SE Asia	Subduction Zone	Eurasian	Continental Crust
12NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Antarctica	Subduction Zone	Scotia	Oceanic Crust
13NR	No Response	0	0	Active	Complex	Intermediate Complex	Andesite, Basalt, Dacite & Rhyolite	Mexico and Central America	Subduction Zone	North American	Continental Crust
14NR	No Response	1	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
15NR	No Response	4	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
16NR	No Response	1	0	Active	Stratovolcano (es)	Intermediate-Mafic	Basalt, Trachyandesite & Trachybasalt	Mediterranean and W Asia	Subduction Zone	African	Continental Crust
17NR	No Response	0	8	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
18NR	No Response	3	0	Active	Caldera	Intermediate-Felsic	Andesite, Dacite & Rhyolite	Japan, Taiwan, Marianas	Subduction Zone	Eurasian	Continental Crust
19NR	No Response	3	0	Active	Stratovolcano	Intermediate-Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
20NR	No Response	0	2	Latent	Stratovolcano	Intermediate-Felsic	Andesite & Dacite	Alaska	Subduction Zone	North American	Intermediate Crust
21NR	No Response	2	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Mexico and Central America	Subduction Zone	North American	Continental Crust
22NR	No Response	0	2	Latent	Stratovolcano	Intermediate	Andesite & Trachyandesite	Indonesia	Subduction Zone	Eurasian	Continental Crust
23NR	No Response	0	1	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	South America	Subduction Zone	South American	Continental Crust
24NR	No Response	0	8	Latent	Stratovolcano (es)	Intermediate-Mafic	Andesite & Basalt	Japan, Taiwan, Marianas	Subduction Zone	Philippine	Oceanic Crust
25NR	No Response	3	0	Active	Stratovolcano	Intermediate-Felsic	Andesite & Dacite	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
26NR	No Response	0	4	Latent	Caldera	Intermediate Complex	Andesite, Basalt & Dacite	Indonesia	Subduction Zone	Eurasian	Continental Crust
27NR	No Response	0	365	Latent	Caldera	Felsic	Rhyolite	South America	Subduction Zone	South American	Continental Crust
28NR	No Response	1	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Rhyolite	South America	Subduction Zone	South American	Continental Crust
29NR	No Response	3	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
30NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
31NR	No Response	2	0	Active	Stratovolcano	Intermediate	Foidite	Africa and Red Sea	Rift Zone	African	Continental Crust
32NR	No Response	0	0	Active	Stratovolcano (es)	Intermediate-Mafic	Basalt, Trachyandesite & Trachybasalt	Mediterranean and W Asia	Subduction Zone	African	Continental Crust
33NR	No Response	0	0	Active	Pyroclastic Shield	Intermediate Complex	Andesite, Basalt & Dacite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
34NR	No Response	0	8	Latent	Shield	Mafic	Basalt	South America	Rift Zone	Nazca	Oceanic Crust
35NR	No Response	0	2	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachybasalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
36NR	No Response	0	0	Active	Complex	Intermediate-Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
37NR	No Response	0	16	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
38NR	No Response	0	2	Latent	Submarine	Intermediate-Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
39NR	No Response	3	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
40NR	No Response	3	0	Active	Stratovolcano (es)	Intermediate	Andesite	Mexico and Central America	Subduction Zone	North American	Continental Crust
41NR	No Response	2	0	Active	Stratovolcano (es)	Intermediate Complex	Andesite, Basalt & Dacite	Mexico and Central America	Subduction Zone	North American	Continental Crust
42NR	No Response	3	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	West Indies	Subduction Zone	Caribbean	Oceanic Crust
43NR	No Response	0	2	Latent	Stratovolcano	Intermediate	Andesite	Indonesia	Subduction Zone	Eurasian	Continental Crust
44NR	No Response	0	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Trachyandesite	Japan, Taiwan, Marianas	Subduction Zone	Philippine	Oceanic Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
45NR	No Response	3	0	Active	Stratovolcano	Intermediate-Felsic	Andesite & Dacite	South America	Subduction Zone	South American	Continental Crust
46NR	No Response	1	0	Active	Shield	Mafic	Basalt	Antarctica	Subduction Zone	Scotia	Oceanic Crust
47NR	No Response	4	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Melanesia and Australia	Subduction Zone	Indo-Australian	Continental Crust
48NR	No Response	0	15	Latent	Shield	Intermediate Complex	Andesite, Basalt & Dacite	Japan, Taiwan, Marianas	Subduction Zone	Eurasian	Continental Crust
49NR	No Response	0	8	Latent	Stratovolcano (es)	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
50NR	No Response	0	0	Active	Stratovolcano	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
51NR	No Response	3	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	West Indies	Subduction Zone	Caribbean	Oceanic Crust
52NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Alaska	Subduction Zone	North American	Continental Crust
53NR	No Response	3	0	Active	Complex	Intermediate-Mafic	Andesite, Basalt & Trachyandesite	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
54NR	No Response	2	0	Active	Stratovolcano (es)	Intermediate Complex	Andesite, Basalt & Dacite	Mexico and Central America	Subduction Zone	North American	Continental Crust
55NR	No Response	3	0	Active	Stratovolcano	Intermediate-Felsic	Andesite & Dacite	Mexico and Central America	Subduction Zone	North American	Continental Crust
56NR	No Response	0	8	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Rhyolite	Iceland and Arctic Ocean	Rift Zone	Eurasian	Oceanic Crust
57NR	No Response	0	2	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Philippines and SE Asia	Subduction Zone	Eurasian	Continental Crust
58NR	No Response	3	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
59NR	No Response	0	12	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kuril Islands	Subduction Zone	Okhotsk	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
60NR	No Response	0	80	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
61NR	No Response	2	0	Active	Lava cone	Intermediate	Andesite	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
62NR	No Response	2	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Dacite	South America	Subduction Zone	South American	Continental Crust
63NR	No Response	2	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Mexico and Central America	Subduction Zone	North American	Continental Crust
64NR	No Response	0	18	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite & Rhyolite	South America	Subduction Zone	South American	Continental Crust
65NR	No Response	0	4	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
66NR	No Response	0	2	Latent	Stratovolcano	Intermediate	Andesite & Trachyandesite	Indonesia	Subduction Zone	Eurasian	Continental Crust
67NR	No Response	0	1	Latent	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite, Trachyandesite & Trachybasalt	Canada and Western USA	Subduction Zone	North American	Continental Crust
68NR	No Response	2	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
69NR	No Response	0	1	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Continental Crust
70NR	No Response	4	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
71NR	No Response	0	0	Active	Stratovolcano	Intermediate	Andesite	Kuril Islands	Subduction Zone	Okhotsk	Intermediate Crust
72NR	No Response	0	3	Latent	Stratovolcano (es)	Intermediate-Felsic	Andesite & Dacite	South America	Subduction Zone	South American	Continental Crust
73NR	No Response	0	34	Latent	Shield	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust

Event ID	Type of Volcanic Response	VEI of Volcanic Activity	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
74NR	No Response	1	0	Active	Stratovolcano	Intermediate Complex	Andesite, Basalt & Rhyolite	South America	Subduction Zone	South American	Continental Crust
75NR	No Response	0	26	Latent	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
76NR	No Response	0	11	Latent	Stratovolcano	Intermediate Complex	Andesite, Rhyolite, Trachyandesite & Trachybasalt	South America	Subduction Zone	South American	Continental Crust
77NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
78NR	No Response	0	0	Active	Stratovolcano (es)	Intermediate	Andesite	Mexico and Central America	Subduction Zone	North American	Continental Crust
79NR	No Response	0	0	Active	Stratovolcano	Intermediate-Mafic	Andesite & Basalt	Indonesia	Subduction Zone	Eurasian	Oceanic Crust
80NR	No Response	0	4	Latent	Shield	Mafic	Basalt	Antarctica	Subduction Zone	Scotia	Oceanic Crust

C

Event ID	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
1NR	546	Along	Dilatation
2NR	310	Along/Perpendicular	Dilatation
3NR	218	Perpendicular	Compression
4NR	716	Along	Dilatation
5NR	190	Perpendicular	Compression
6NR	384	Along	Dilatation
7NR	238	Along	Compression
8NR	776	Along/Perpendicular	Dilatation
9NR	526	Along	Dilatation

Event ID	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
10NR	769	Along	Dilatation
11NR	603	Perpendicular	Compression
12NR	632	Perpendicular	Compression
13NR	89	Perpendicular	Dilatation
14NR	119	Perpendicular	Dilatation
15NR	159	Along	Compression
16NR	508	Perpendicular	Dilatation
17NR	866	Along	Dilatation
18NR	621	Along/Perpendicular	Dilatation
19NR	436	Along	Compression
20NR	661	Along	Dilatation
21NR	533	Along	Compression
22NR	913	Along	Dilatation
23NR	434	Along	Compression
24NR	416	Along/Perpendicular	Compression
25NR	621	Along	Compression
26NR	816	Perpendicular	Dilatation
27NR	673	Perpendicular	Compression
28NR	934	Perpendicular	Compression
29NR	356	Perpendicular	Compression
30NR	416	Along	Compression
31NR	529	Along	Dilatation
32NR	757	Perpendicular	Dilatation
33NR	129	Perpendicular	Dilatation
34NR	720	Perpendicular	Dilatation
35NR	677	Along	Compression
36NR	308	Along	Dilatiaton
37NR	569	Perpendicular	Dilatation
38NR	886	Along	Dilatation
39NR	449	Along	Compression

Event ID	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
40NR	288	Along	Compression
41NR	265	Perpendicular	Compression
42NR	652	Perpendicular	Compression
43NR	615	Along	Dilatation
44NR	520	Along	Compression
45NR	659	Along	Dilatation
46NR	393	Perpendicular	Dilatation
47NR	664	Perpendicular	Dilatation
48NR	654	Along	Dilatation
49NR	792	Along	Compression
50NR	404	Along	Dilatation
51NR	221	Along	Compression
52NR	522	Along/Perpendicular	Compression
53NR	999	Perpendicular	Dilatation
54NR	545	Along	Dilatation
55NR	168	Along/Perpendicular	Dilatation
56NR	64	Perpendicular	Compression
57NR	802	Along	Dilatation
58NR	805	Along	Compression
59NR	381	Perpendicular	Compression
60NR	497	Along	Dilatation
61NR	999	Along	Compression
62NR	916	Along	Compression
63NR	160	Perpendicular	Compression
64NR	905	Along/Perpendicular	Compression
65NR	232	Along	Compression
66NR	297	Perpendicular	Compression
67NR	938	Along/Perpendicular	Compression
68NR	300	Along	Compression
69NR	589	Perpendicular	Compression

Event ID	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
70NR	655	Perpendicular	Compression
71NR	533	Along	Compression
72NR	145	Along	Dilatation
73NR	760	Perpendicular	Dilatation
74NR	169	Perpendicular	Dilatation
75NR	648	Along	Compression
76NR	453	Along/Perpendicular	Dilatation
77NR	896	Along	Compression
78NR	586	Perpendicular	Compression
79NR	447	Along	Compression
80NR	290	Perpendicular	Dilatation

APPENDIX VI

DIVISION OF EARTHQUAKE-VOLCANO PARAMETERS INTO TRAINING AND TEST DATA FOR MACHINE LEARNING ANALYSES

Objective Field	Training Samples (70%)		Test Sample (30%)	
	Response Case Studies	Non-Response Case Studies	Response Case Studies	Non-Response Case Studies
Interaction (Response or No Response)	1R, 2R, 3R, 4R, 5R, 6R, 7R, 9R, 10R, 17R, 18R, 20R, 22R, 23R, 24R, 25R, 26R, 27R, 28R, 30R, 32R, 37R, 38R, 39R, 41R, 43R, 44R, 46R, 47R, 48R, 50R, 51R, 52R, 54R, 55R, 56R, 57R, 58R, 59R, 60R, 61R, 62R, 63R, 64R, 65R, 66R, 67R, 68R, 69R, 70R, 71R, 72R, 73R, 74R, 75R, 78R, 79R, 82R, 84R	1NR, 2NR, 3NR, 4NR, 5NR, 6NR, 8NR, 9NR, 10NR, 11NR, 12NR, 15NR, 17NR, 19NR, 21NR, 22NR, 23NR, 25NR, 26NR, 27NR, 29NR, 30NR, 33NR, 36NR, 38NR, 39NR, 40NR, 41NR, 42NR, 43NR, 44NR, 45NR, 46NR, 47NR, 48NR, 50NR, 51NR, 52NR, 54NR, 55NR, 56NR, 57NR, 58NR, 59NR, 61NR, 63NR, 67NR, 68NR, 69NR, 71NR, 73NR, 74NR, 75NR, 76NR, 77NR, 79NR	8R, 11R, 12R, 13R, 14R, 15R, 16R, 19R, 21R, 29R, 31R, 33R, 34R, 35R, 36R, 40R, 42R, 45R, 49R, 53R, 76R, 77R, 80R, 81R, 83R, 85R	7NR, 13NR, 14NR, 16NR, 18NR, 20NR, 24NR, 28NR, 31NR, 32NR, 34NR, 35NR, 37NR, 49NR, 53NR, 60NR, 62NR, 64NR, 65NR, 66NR, 70NR, 72NR, 78NR, 80NR

Change in Volcanic Radiant Flux (%)	1R, 2R, 3R, 5R, 6R, 7R, 8R, 12R, 13R, 14R, 16R, 17R, 20R, 23R, 24R, 25R, 27R, 29R, 30R, 31R, 32R, 33R, 35R, 36R, 39R, 40R, 42R, 43R, 44R, 46R, 47R, 48R, 49R, 50R, 51R, 52R, 53R, 54R, 55R, 57R, 58R, 59R, 61R, 62R, 63R, 65R, 66R, 67R, 69R, 72R, 74R, 75R, 76R, 77R, 80R, 82R, 83R, 84R, 85R	N/A	4R, 9R, 10R, 11R, 15R, 18R, 19R, 21R, 22R, 26R, 28R, 34R, 37R, 38R, 41R, 45R, 56R, 60R, 64R, 68R, 70R, 71R, 73R, 78R, 79R, 81R	N/A
Temporal Delay (Days)	2R, 3R, 5R, 6R, 8R, 10R, 11R, 12R, 14R, 15R, 16R, 17R, 18R, 19R, 20R, 22R, 24R, 25R, 26R, 28R, 29R, 30R, 32R, 33R, 35R, 37R, 38R, 40R, 41R, 43R, 44R, 45R, 46R, 47R, 48R, 49R, 50R, 52R, 53R, 54R, 55R, 56R, 57R, 59R, 62R, 63R, 64R, 65R, 69R, 71R, 72R, 73R, 75R, 76R, 80R, 81R, 82R, 83R, 84R	N/A	1R, 4R, 7R, 9R, 13R, 21R, 23R, 27R, 31R, 34R, 36R, 39R, 42R, 51R, 58R, 60R, 61R, 66R, 67R, 68R, 70R, 74R, 77R, 78R, 79R, 85R	N/A

Length of Response (Days)	1R, 2R, 3R, 4R, 5R, 6R, 7R, 8R, 9R, 10R, 12R, 14R, 15R, 16R, 17R, 18R, 19R, 20R, 22R, 23R, 25R, 26R, 28R, 29R, 30R, 31R, 34R, 35R, 37R, 38R, 39R, 40R, 41R, 43R, 44R, 45R, 47R, 48R, 50R, 51R, 52R, 53R, 54R, 55R, 61R, 62R, 65R, 66R, 68R, 70R, 74R, 75R, 77R, 78R, 79R, 80R, 81R, 82R, 85R	N/A	11R, 13R, 21R, 24R, 27R, 32R, 33R, 36R, 42R, 46R, 49R, 56R, 57R, 58R, 59R, 60R, 63R, 64R, 67R, 69R, 71R, 72R, 73R, 76R, 83R, 84R	N/A

APPENDIX VII

EARTHQUAKE AND VOLCANO PARAMETERS OF PREDICTION CASE STUDIES

Prediction ID	Earthquake Rupture Length (km)	Earthquake Depth (km)	Azimuth (°)	Earthquake Strike (°)	Earthquake Dip (°)	Type of Earthquake Fault	Incoming Earthquake Wave Direction	Region of Earthquake	Tectonic Plate of Earthquake's Location
1P	65.6	33.0	45	148	61	Reverse (Thrust)	South West	-	Indo-Australian
2P	40.7	70.0	300	309	43	Normal	South East	North America	North American
3P	13.4	57.7	299	84	56	Reverse (Thrust)	South East	Indonesia	Indo-Australian
4P	-	29.0	226	25	80	Reverse (Thrust)	North East	Asia	Okhotsk
5P	15.7	12.5	360	323	77	Strike-Slip	South	Indonesia	Eurasian
6P	15.7	12.5	94	323	77	Strike-Slip	West	Indonesia	Eurasian
7P	40.7	66.0	344	267	90	Oblique Reverse	South	North America	North American
8P	-	22.9	75	19	18	Reverse (Thrust)	South West	South America	South American
9P	13.4	66.0	285	201	44	Oblique Reverse	South East	Europe	Eurasian
10P	65.6	1.1	332	341	70	Strike-Slip	South East	North America	North American
11P	9.7	9.0	294	140	46	Normal	South East	Melanesia	-
12P	29.6	12.0	160	160	89	Strike-Slip	North West	Melanesia	-
13P	9.7	30.0	284	39	66	Reverse (Thrust)	South East	Russia	-
14P	11.4	21.0	257	281	22	Reverse (Thrust)	South West	Central America	-
15P	18.4	20.0	58	333	80	Normal	South West	North America	-
16P	11.4	41.5	164	19	17	Reverse (Thrust)	North West	South America	-
17P	11.4	41.5	170	19	17	Reverse (Thrust)	North West	South America	-
18P	18.4	119.0	33	10	71	Strike-Slip	South West	Russia	-
19P	21.6	29.0	12	132	57	Reverse (Thrust)	South West	Melanesia	-
20P	15.7	32.0	170	5	26	Reverse (Thrust)	South East	South America	-

Prediction ID	Time Since Last Period of Volcanic Activity (Years)	Status of Volcano at Time of Earthquake	Volcano Type	Magma Composition	Surrounding Volcanic Geology	Region of Volcano	Tectonic Setting of Volcano's Location	Tectonic Plate of Volcano's Location	Type of Crust of Volcano's Location
1P	0	-	Stratovolcano	Intermediate	Andesite and Basalt	-	-	Indo-Australian	-
2P	0	-	Stratovolcano	Intermediate Complex	Andesite, Basalt and Dacite	-	-	North American	-
3P	0	-	Complex	Intermediate Mafic	Andesite and Basalt	-	-	Indo-Australian	-
4P	303	-	Stratovolcano	Intermediate Complex	Andesite, Basalt and Dacite	-	-	Eurasian	-
5P	0	-	Stratovolcano	Intermediate	Andesite and Trachyandesite	-	-	Eurasian	-
6P	0	-	Stratovolcano	Intermediate Mafic	Andesite and Basalt	-	-	Eurasian	-
7P	87	-	Stratovolcano	Intermediate Complex	Andesite, Basalt, Dacite and Rhyolite	-	-	North American	-
8P	43	-	Stratovolcano	Intermediate Complex	Andesite, Basalt and Dacite	-	-	South American	-
9P	0	-	Stratovolcano	Intermediate Mafic	Basalt, Trachyandesite and Trachybasalt	-	-	African	-
10P	10000	-	Caldera	-	-	-	-	North American	-
11P	2	Latent	Stratovolcano	-	-	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
12P	0	On-Going	Pyroclastic Shield	-	-	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
13P	3	Latent	Caldera	-	-	Kamchatka and Mainland Asia	Subduction Zone	Okhotsk	Continental Crust
14P	0	On-Going	Stratovolcano	-	-	Central America	Subduction Zone	North American	Continental Crust
15P	0	On-Going	Stratovolcano	-	-	Alaska	Subduction Zone	North American	Continental Crust

16P	0	On-Going	Stratovolcano	-	-	South America	Subduction Zone	South American	Continental Crust
17P	1	Latent	Stratovolcano	-	-	South America	Subduction Zone	South American	Continental Crust
18P	3	Latent	Shield	-	-	Japan, Taiwan, Marianas	Subduction Zone	Eurasian	Continental Crust
19P	0	On-Going	Lava Cone	-	-	Melanesia and Australia	Subduction Zone	Indo-Australian	Intermediate Crust
20P	6	Latent	Shield	-	-	South America	Rift Zone	Nazca	Oceanic

Prediction ID	Type of Crust of Volcano's Location	Distance (km)	Location of Volcano in Relation to Earthquake	Volcanic Compression or Dilatation
1P	-	80	-	Dilatation
2P	-	143	Perpendicular	Compression
3P	-	124	Perpendicular	Dilatation
4P	-	456	Perpendicular	Compression
5P	-	48	Perpendicular	Dilatation
6P	-	272	Perpendicular	Compression
7P	-	100	Perpendicular	Compression
8P	-	199	Perpendicular	Compression
9P	-	746	Perpendicular	Dilatation
10P	-	446	Perpendicular	Compression
11P	Intermediate Crust	69	-	Compression
12P	Intermediate Crust	645	-	Compression
13P	Continental Crust	142	-	Dilatation
14P	Continental Crust	255	-	Dilatation
15P	Continental Crust	956	-	Dilatation
16P	Continental Crust	475	-	Dilatation
17P	Continental Crust	597	-	Dilatation
18P	Continental Crust	602	-	Compression
19P	Intermediate Crust	58	-	Dilatation
20P	Oceanic	334	-	Dilatation

APPENDIX VIII

MULTIPLE REGRESSION ANALYSES OF EARTHQUAKE-VOLCANO INTERACTIONS

Table VI presents the results of multiple regression analysis in which the effect of each parameter identified in Appendix IV on a volcano's response are examined. The adjusted R^2 shows that in 36.2% of cases the earthquake-volcano interactions examined can be predicted based on parameters in this thesis. In support of these findings, $F = 10.304$, $p > 0.000$ indicates that the multiple regression model is statistically significant and can, to some extent, predict an outcome based on the independent parameters in this model. However, when each parameter is considered independently (Significance of Predictor Values) there are no parameters that have a significant influence over a volcano's response.

TABLE VI SUMMARY STATISTICS FROM MULTIPLE REGRESSION ANALYSIS WHERE TRIGGERED OR NON-TRIGGERED ACTIVITY IS THE DEPENDENT VARIABLE.

$F\,(10, 154) = 10.304,\ p < 0.005,\ R^2 = 0.401$

MODEL SUMMARY

R	R^2	ADJUSTED R^2	STANDARD ERROR OF THE ESTIMATE
0.633	0.401	0.362	0.400

ANOVA

Model	Sum of Squares	df	Mean Square	F	*p*-value
Regression	16.521	10	1.652	10.304	0.000
Residual	24.691	154	0.160		
Total	41.212	164			

Significance of Predictor Values*

Model	B	Beta	*p*-value
Earthquake Magnitude	-0.029	0.090	0.982
Earthquake Rupture Length	-0.001	-0.057	0.718
Earthquake Depth	0.000	-0.049	0.460
Temporal Delay	-0.003	-0.390	0.000
Length of Response	-0.001	-0.420	0.000
Time Since Last Activity	2.352×10^{-5}	0.060	0.358
Distance	-1.759×10^{-5}	-0.009	0.890
Earthquake Azimuth to Volcano	0.000	0.025	0.690
Earthquake Strike	0.000	-0.073	0.262
Earthquake Dip	0.000	0.015	0.778

*Only parameters identified to influence the model outcome are included

APPENDIX IX

ETHICAL APPROVAL

Project Information
Project Ref: **P7126**

Full name: Charley Hill-Butler

Faculty: [BES] Business, Environment and Society

Department: [BESA1G] BES Geography, Environment and Disaster Management

Module Code:

Supervisor: Matthew Blackett

Project title: **A Remote Sensing Approach to Investigate Relationships between Earthquakes and Volcanic Activity**

Date(s): 17/09/2012 - 13/09/2015

Created: 24/09/2012 10:47

Project Information: This research project will use secondary datasets to examine the response of volcanoes to earthquakes. The datasets will be sourced from government bodies and academic sources (e.g. NASA and the USGS) and used in a desk based analysis.

Participants in your research		
1	Will the project involve human participants?	No

Risk to Participants		
1	Will the project involve human patients/clients, health professionals, and/or patient (client) data and/or health professional data?	No
2	Will any invasive physical procedure, including collecting tissue or other samples, be used in the research?	No
3	Is there a risk of physical discomfort to those taking part?	No
4	Is there a risk of psychological or emotional distress to those taking part?	No
5	Is there a risk of challenging the deeply held beliefs of those taking part?	No
6	Is there a risk that previous, current or proposed criminal or illegal acts will be revealed by those taking part?	No
7	Will the project involve giving any form of professional, medical or legal advice, either directly or indirectly to those taking part?	No

Risk to Researcher		
1	Will this project put you or others at risk of physical harm, injury or death?	No
2	Will project put you or others at risk of abduction, physical, mental or sexual abuse?	No
3	Will this project involve participating in acts that may cause psychological or emotional distress	No

Risk to Researcher		
	to you or to others?	
4	Will this project involve observing acts which may cause psychological or emotional distress to you or to others?	No
5	Will this project involve reading about, listening to or viewing materials that may cause psychological or emotional distress to you or to others?	No
6	Will this project involve you disclosing personal data to the participants other than your name and the University as your contact and e-mail address?	No
7	Will this project involve you in unsupervised private discussion with people who are not already known to you?	No
8	Will this project potentially place you in the situation where you may receive unwelcome media attention?	No
9	Could the topic or results of this project be seen as illegal or attract the attention of the security services or other agencies?	No
10	Could the topic or results of this project be viewed as controversial by anyone?	No
11	Does the project involve the researcher travelling outside the UK?	No

Informed Consent of the Participant		
1	Are any of the participants under the age of 18?	No
2	Are any of the participants unable mentally or physically to give consent?	No
3	Do you intend to observe the activities of individuals or groups without their knowledge and/or informed consent from each participant (or from his or her parent or guardian)?	No

Participant Confidentiality and Data Protection		
1	Will the project involve collecting data and information from human participants who will be identifiable in the final report?	No
2	Will information not already in the public domain about specific individuals or institutions be identifiable through data published or otherwise made available?	No
3	Do you intend to record, photograph or film individuals or groups without their knowledge or informed consent?	No
4	Do you intend to use the confidential information, knowledge or trade secrets gathered for any purpose other than this research project?	No

Gatekeeper Protection		
1	Will this project involve collecting data outside University buildings?	No
2	Do you intend to collect data in shopping centres or other public places?	No
3	Do you intend to gather data within nurseries, schools or colleges?	No
4	Do you intend to gather data within National Health Service premises?	No

Other Ethical Issues

1	Is there any other risk or issue not covered above that may pose a risk to you or any of the participants?	No
2	Will any activity associated with this project put you or the participants at an ethical, moral or legal risk?	No

Principal Investigator's Declaration

I believe that this project **does not require research ethics approval**. I have completed the checklist and kept a copy for my own records. I realise I may be asked to provide a copy of this checklist at any time.	Yes
I confirm that I have answered all relevant questions in this checklist honestly.	Yes
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request a new ethical approval if the project subsequently changes the information I have given in this checklist.	Yes

Attachments

Participant Information Leaflet.	-
Informed Consent Form.	-
Health & Safety Assessment attached.	-

Step	Status	Authoriser	Authorised on
Supervisor	Approved	Matthew Blackett	Mon, 24 Sep 2012 12:43 PM
Referrer	Not required		